NASA Contractor Report 198286

Strain Gage Selection Criteria for Textile Composite Materials

John E. Masters
Lockheed Martin Engineering and Sciences Company, Hampton, Virginia

Contract NAS1-19000

February 1996

National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

Abstract:

Composite materials reinforced with braided, woven, knit, and stitched fibrous preforms are emerging as potential alternatives to unidirectional prepreg tape. A variety of these material forms are currently being evaluated by major airframe manufacturers.

These new forms of composite materials bring with them potential testing problems. The applicability of existing test methods to the 2-D and 3-D braided, woven, stitched, and knit materials being evaluated bears investigation. The overriding concern is that the values measured are accurate representations of the true material response.

This report will provide a review of efforts to establish a set of strain gage selection guidelines for textile reinforced composite materials.

A variety of strain gages were evaluated in the study to determine the sensitivity of strain measurements to the size of the strain gage. The strain gages were chosen to provide a range of gage lengths and widths. The gage aspect ratio (the length-to-width ratio) was also varied.

The gages were tested on a diverse collection of textile composite laminates. Test specimens featured eleven different textile architectures: four 2-D triaxial braids, six 3-D weaves, and one stitched uniweave architecture. All specimens were loaded in uniaxial tension. The materials' moduli were measured in both the longitudinal (parallel to the 0° yarns) and the transverse (perpendicular to the 0° yarns) directions. The results of these measurements were analyzed to establish the strain gage guidelines.

Introduction

NASA's Advanced Composite Technology (ACT) Program was initiated in 1990 with the purpose of developing less costly composite aircraft structures. A number of innovative materials and processes have been evaluated as a part of this effort. Chief among them are composite materials reinforced with textile preforms. Composite laminates reinforced with continuous networks of braided, woven, knit, or stitched fibers have been evaluated as a part of the program. The viability of these material forms as potential alternatives to unidirectional prepreg tape has been established as a consequence.

These new composite material forms bring with them potential testing problems. The fiber architecture plays a prime role in determining the mechanical response of these braided, woven, and stitched materials. Test methods currently used to evaluate composite materials were developed for composite materials made of unidirectional prepreg tape or simple 2-D woven fabrics. The microstructure of these laminated composite materials differs significantly from the textile composites evaluated in the ACT program. Consequently, the applicability of the current test methods to the wide range of emerging materials bears investigation. The overriding concern is that the values measured are accurate representations of the true material response.

A textile composite's preform architecture presents a variety of size effects that are not encountered in tape laminates. A convenient way to analyze a textile composite is to consider a unit cell of the material. A unit cell is defined as the smallest unit of repeated fiber architecture. It may be considered the building block of the material. The size of the unit cell is dependent on a number of factors including the size of the yarns, the angle at which they are intertwined or interwoven, and the intricacy of the braid or weave pattern.

A representative volume of material must be tested and monitored to accurately reflect true material response. Specimen geometry and strain gage size must be reexamined in terms of unit cell size. The effect of the sizes of the yarn bundles within the preform must also be considered since they may also effect the performance and the measurements. Specimen dimensions established for tape type composites may not be applicable to textile composites. The degree of heterogeneity present in the latter materials is quite different from that encountered in the former. The potential effects of these differences must also be quantified.

A program to establish a set of test methods to evaluate textile composites was developed to address these size effect issues. This report will provide a review of a portion of that work, the effort to establish a set of strain gage selection guidelines for textile reinforced composite materials.

Moiré interferometry was used to assess the degree of heterogeneity present in textile composites [Ref. 1]. The technique, which defines deformation patterns in both the vertical and horizontal directions, was used to define the full field strain distribution in a variety of textile composite systems. It was applied to specimens subjected to longitudinal and transverse tensile loading. Examples of the results obtained for a 2-D triaxially braided laminate are shown in Figures 1-5.

Figure 1 illustrates the geometry of the specimens investigated in the interferometry studies. The vertical displacement field that resulted when a specimen was loaded to 1200 micro-strain along the 0° fiber direction is also shown in the figure.

The vertical displacement fields (V fields) consist of basically horizontal fringes that indicate specimen extension. Points along one fringe have been displaced vertically with respect to points along a neighboring fringe. For a uniform extension the fringes should be evenly spaced and straight. The fringes for the specimens tested are, however, wavy and the spacing between them varies. The variation is cyclic and coincides with the repeated unit of the textile architecture.

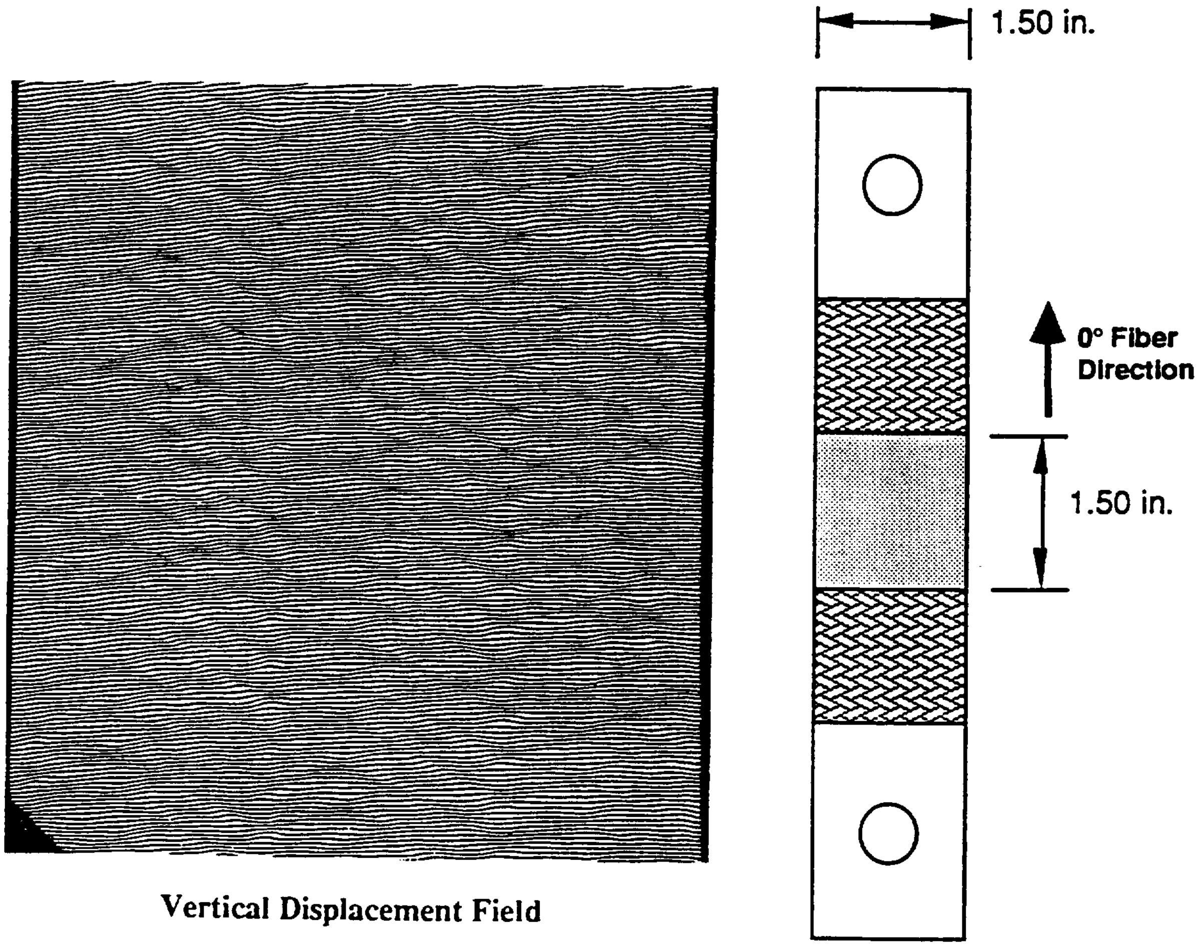


Figure 1. Vertical Displacement Field in a 2-D Triaxially Braided Laminate Loaded in Longitudinal Tension.

A typical horizontal displacement pattern (U field) found in these specimens when subjected to axial tensile loading is shown in Figure 2. It consists of zigzag vertical fringes that display the Poisson's effect. For uniform contraction the fringes should be straight and the spacing constant. However, the fringes display a cyclic variation that matches the braid geometry. The sharp kinks in the U field fringes reveal the presence of shear strains between the fiber bundles.

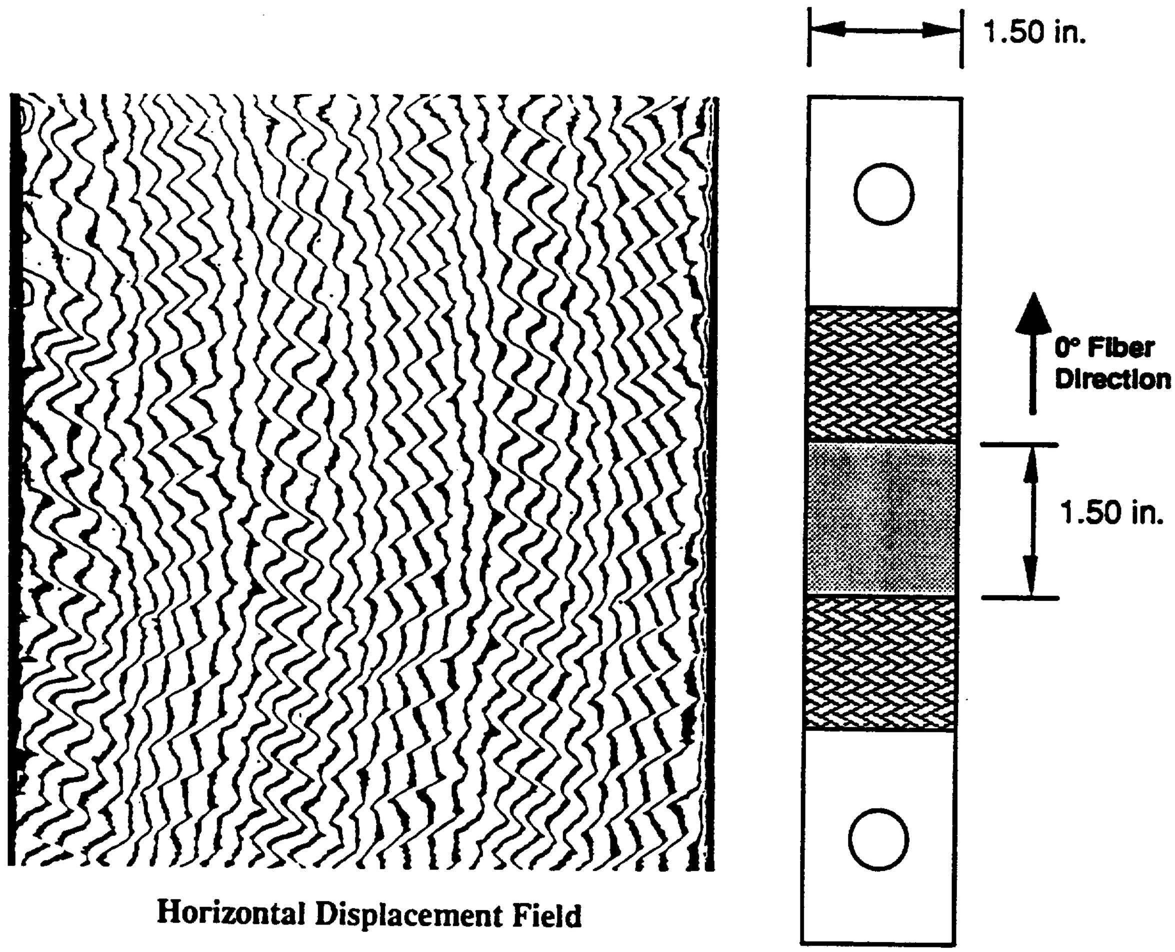
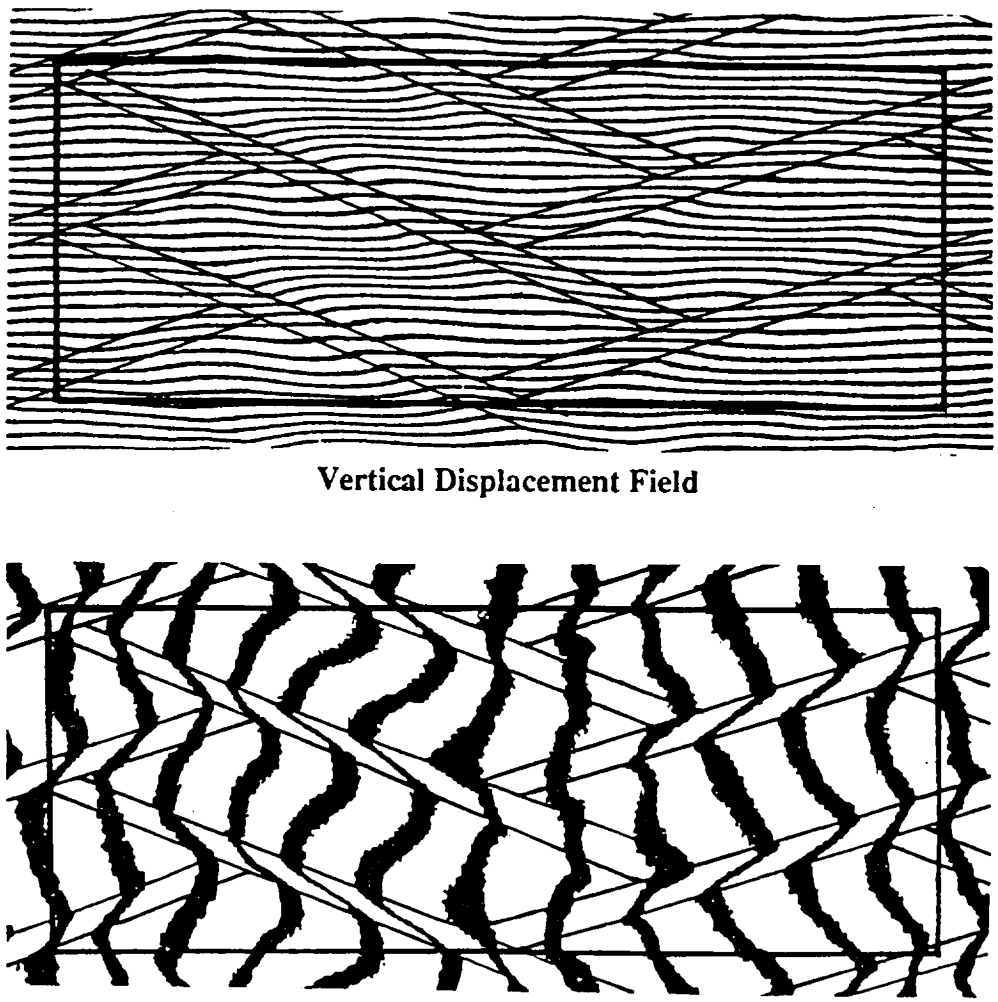


Figure 2. Horizontal Displacement Field in a 2-D triaxially Braided Laminate Loaded in Longitudinal Tension.

Figure 3 shows the V and U fields of a highly magnified region of the specimen, in each case focusing on two unit cells of material. The boundaries between adjacent fiber bundles and the outline of the cells are marked. The figure reveals that the shear deformation that develops at the interfaces between the fiber bundles occurs over a finite width. This width is illustrated in the patterns as the distance between the closely spaced lines. This is consistent with the presence of resin rich areas between the fiber bundles, which are about one fifth of the width of the fiber bundle itself. The U field shows that in the resin rich zones the shear strain, γ_{xy}, is approximately 0.5 times that of the average applied normal strain, ε_y. Additionally, the U field shows that the Poisson effect was nearly constant across the unit cell. The V displacement pattern clearly shows that the ε_y strain varies significantly within each unit cell as can be seen by the nonuniform fringe spacing. The ratio of maximum to minimum ε_y strain was about 2 to 1. The normal strain varies on top of the fiber bundles and is nearly constant throughout all the resin rich zones.



Vertical Displacement Field

Horizontal Displacement Field

Figure 3. Vertical and Horizontal Displacement Fields in a 2-D Triaxially Braided Laminate.

Interferometry was also performed on specimens loaded in the transverse direction (i.e., at 90° to the axial direction). Figure 4 shows the region investigated in these specimens. The pattern of the surface braided yarns are shown schematically in the figure. The deformation fields that developed in these coupons are shown in the next figure.

In general, the interferometry results indicate that greater variations in normal and shear strains existed in specimens loaded in the transverse direction than in the axial direction.

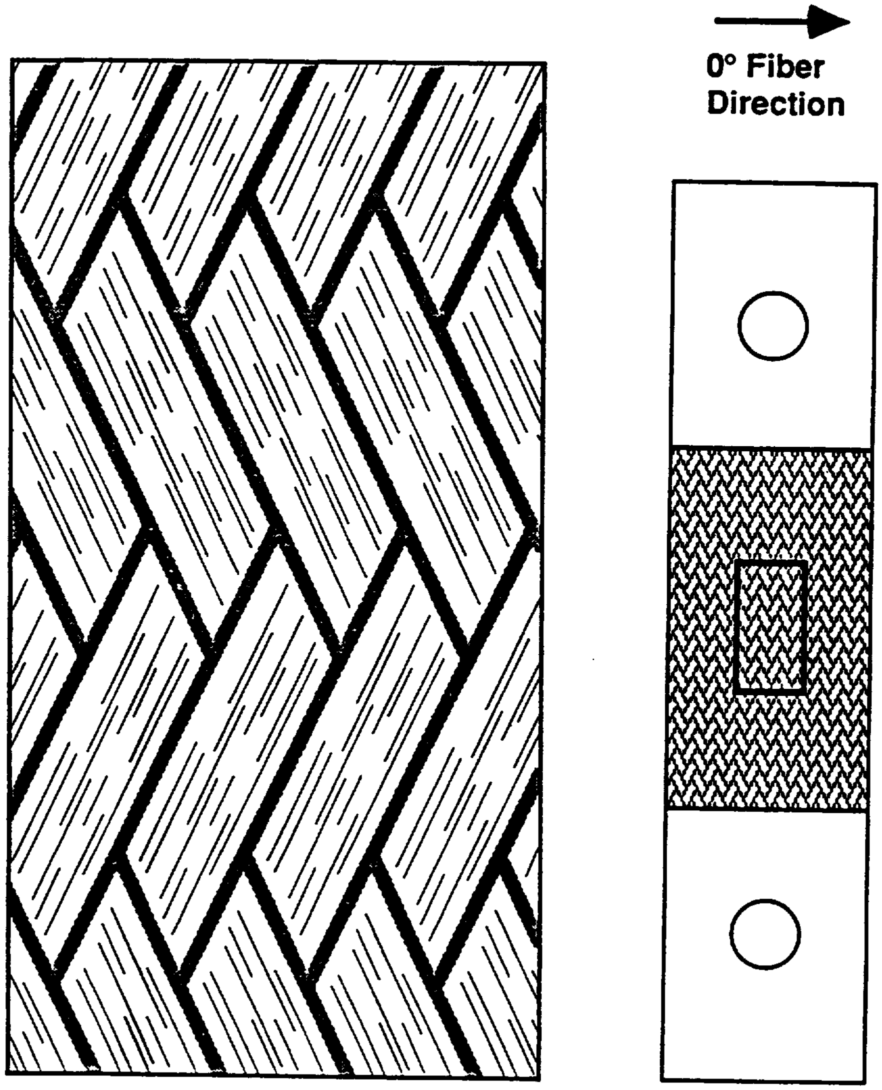


Figure 4. Test Specimen and Fiber Architecture of a 2-D Triaxially Braid Loaded in Transverse Tension.

Figure 5 displays the vertical displacement field for a coupon loaded in the transverse direction. The locations of the yarns are evident in the vertical displacement fringe patterns. The sudden jogs in the fringes represent strong shear strains in the resin rich regions between the yarns. From the V displacement pattern, the spacing of the fringes in the vertical direction displays a cyclic variation. The strains are highest over the region where there are 90° fibers under the braider yarns. They are lowest over the regions where the braider yarns cross. The average strains in these two regions differ by a factor of three.

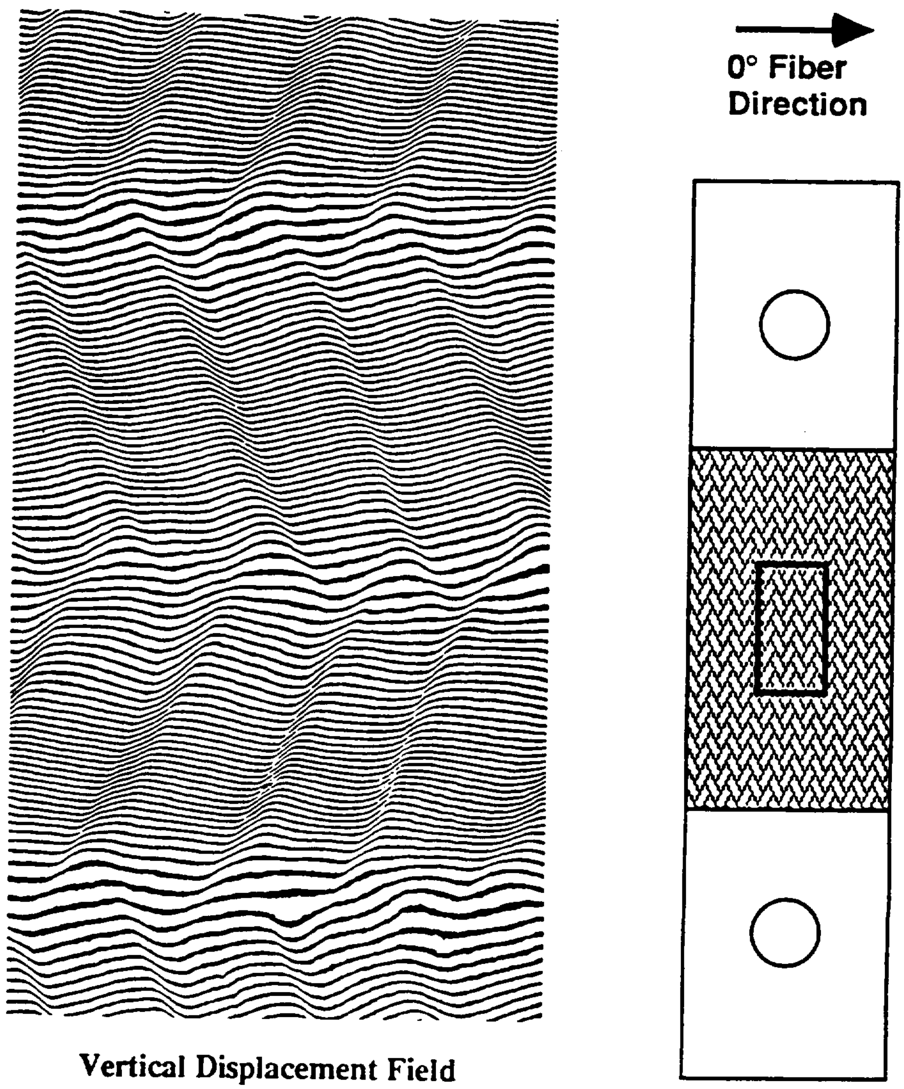


Figure 5. Vertical Displacement Field in a 2-D Triaxially Braided Laminate Loaded in Transverse Tension.

Unlike the axial loading case, the cyclic variation seen in these specimens is not confined to the dimensions of the unit cell. The variation breaches the unit cell to form a global material response that covers the entire specimen. This is illustrated by the horizontal bands seen in the figure. They span several unit cells and extend across the specimen width.

The preceding figures illustrate the significance of the variations in displacement field homogeneity that have been identified in braided textile composite specimens. Test specimens must, therefore, be designed to encompass representative volumes of material within their test sections to obtain characteristic measures of mechanical response. The size and type of instrumentation used plays a similarly critical role in obtaining accurate measurements.

There are, of course, two common methods of instrumenting test specimens: strain gages and extensometers. Extensometers provide a more global measure of material response and will cost less in the long run since they are reusable. They are, however, not applicable to all test situations. For example, although suitable for coupon testing, extensometers cannot be easily mounted to large test panels. They can also be limiting since the specimens cannot be handled once the extensometers have been mounted, as this would in most cases disturb the continuity of their measurements. Strain gages are more versatile; they can be applied to a wider variety of test situations. They are permanently affixed to the specimen and, therefore, permit its removal from the test machine for inspection, etc. Strain gages do, however, provide only a local measure of the material response and are, therefore, subject to local inhomogeneity. In particular, the local displacement fields that develop in textile composites present a special challenge to strain gage usage. This latter problem was one of the subjects of this investigation.

A series of tensile tests was conducted to establish performance levels of extensometers and strain gages on textile composites and to determine the sensitivity of strain measurements to the size of the strain gage. This report will review the results of that study.

The following sections include descriptions of the materials investigated in the study, the experimental procedures employed, and the test specimen geometries and strain gages used. A discussion of the experimental results will then be presented. This is followed by a summary that discusses instrumentation practices and defines strain gage selection criteria for textile composite materials.

Materials Investigated

The program investigated the three material types evaluated in Phase B of the ACT Program: 2-D triaxial braids, through-the-thickness weaves, and stitched uniwoven laminates. The braided and woven laminates featured braided AS-4 yarns that were impregnated with Shell 1895 epoxy resin. The stitched laminates featured AS-4 fibers and Hercules 3501-6 epoxy resin.

Braided Material

In a triaxially braided preform three yarns are intertwined to form a single layer of $0°/\pm\Theta°$ material. In this case, the braided yarns are intertwined in a 2 x 2 pattern. Each $+\Theta$ yarn crosses alternatively over and under two $-\Theta$ yarns and vice verse. The 0° yarns were inserted between the braided yarns. This yields a two-dimensional material; there is not through-the-thickness reinforcement. Figure 6 schematically illustrates the fiber architecture and establishes the nomenclature used in the paper.

The yarns were braided over a cylindrical mandrel. The desired preform thickness was achieved by overbraiding layers; there are no through-the-thickness fibers. After braiding, the preforms were removed from the mandrel, slit along the 0° fiber direction, flattened, and border stitched to minimize fiber shifting. The resin was introduced through a resin transfer molding process.

The figure shows a repeatable unit of the braid architecture that is sometimes referred to as the braid's natural unit cell. As was stated earlier, a unit cell is a repeatable unit of fabric geometry. It represents the complete yarn or tow intertwinement pattern. It is desirable, for analysis purposes, to define the smallest unit cell possible. Rectangular unit cells are also preferable. The box outlined within the rhombic unit cell defines the smallest unit cell for a 2/2 triaxial braid.

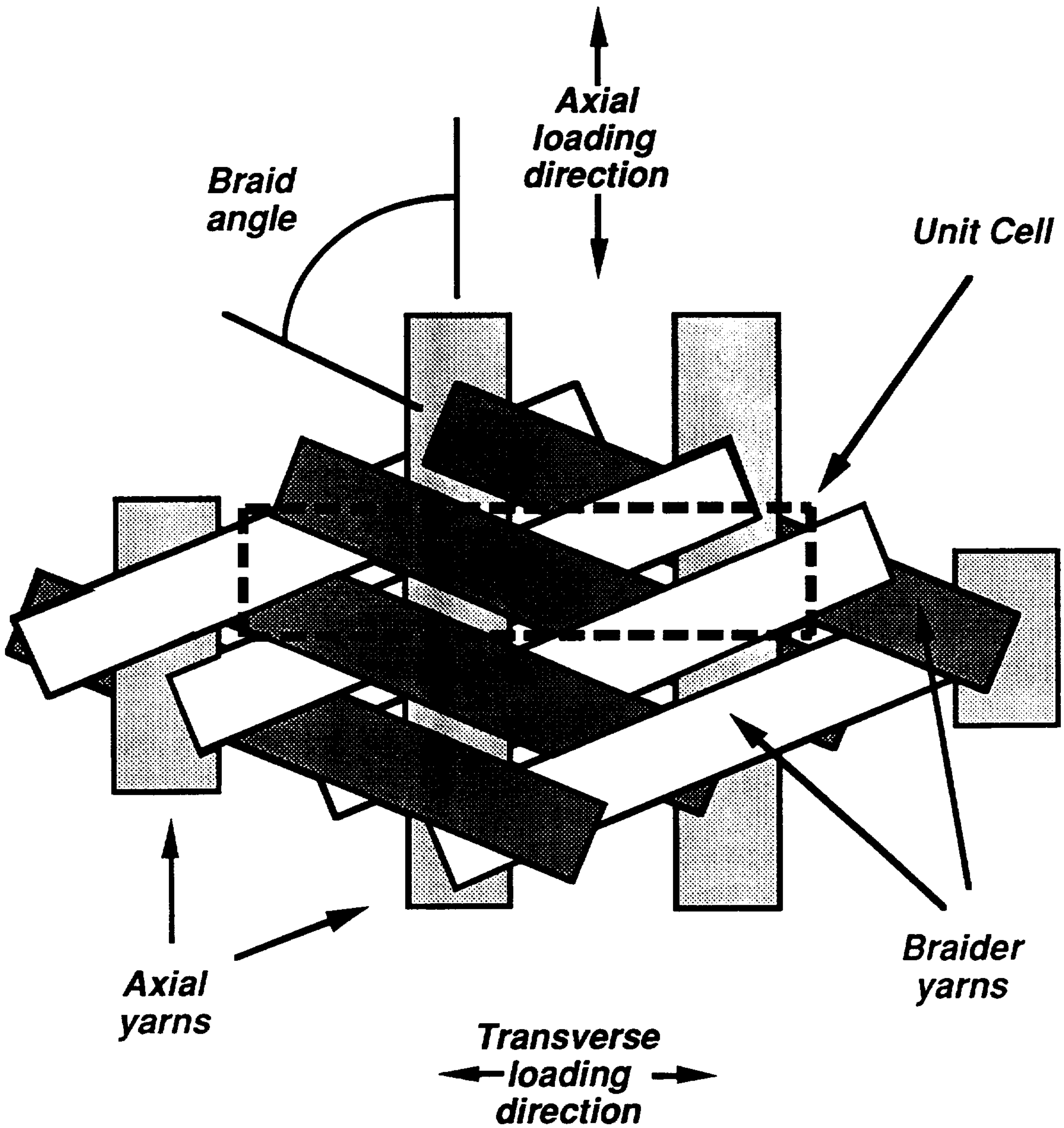


Figure 6. Triaxial Braid Configuration and Nomenclature.

In a braid, the unit cell width is dependent on mandrel diameter and the number of yarns braided. The height of the unit cell is dependent on the cell width and the braid angle. The sizes of the minimum unit cells for the braids tested in this study are summarized in Table I. The significance of these dimensions will be discussed further in the following section.

Table I. 2-D Triaxial Braid Configurations Investigated.

Material Type	0° Yarn Spacing (Yarn/inch)	Braider Yarn Spacing (Yarn/inch)	Mandrel Diam. (inch)	Number of Layers	Unit Cell Size (inch) height x width
$[0_{30k} / \pm 70_{6k}]$ 46% Axial	4.3	12.5	5.25	4	.083 x .458
$[0_{75k} / \pm 70_{15k}]$ 46% Axial	2.4	6.9	4.75	3	.150 x .829
$[0_{36k} / \pm 45_{15k}]$ 46% Axial	4.7	6.7	4.75	3	.207 x .414
$[0_{6k} / \pm 45_{15k}]$ 12% Axial	4.7	6.7	4.75	5	.207 x .414

Note: $[0_{75k}/\pm 70_{15k}]$ 46% Axial laminates were braided with 72 braider and 36 axial yarns. "k" indicates thousands. The fiber diameter of AS-4 equals 7 microns.

Four 2-D triaxial braid architectures were tested. They were designed to provide direct measures of the braid sensitivity to the braid angle, the yarn sizes, and the longitudinal yarn content. The nominal braid configurations are summarized in Table I. In addition to the three parameters listed above, the table also lists the nominal spacing of the longitudinal and braid yarns and their mandrel diameters. Since all specimens were to have a nominal thickness of 0.125 inch, the number of layers increased as yarn bundle size decreased. The number of lamina in each laminate are also listed in the table. It should be noted that these architectures were chosen to define the extremes of the family of 2-D triaxial braids. Emphasis was given in their design to providing a wide range of mechanical properties to support analytical model development.

A shorthand notation, similar to the practice used to define the stacking sequence of laminates formed of unidirectional prepreg tape, is introduced in the table to define the braid architecture. This notation will be employed throughout the report when referring to the braided laminate test results.

The proposed notation is

$$[0^\circ \ xk \ / \pm \Theta^\circ \ yk] \ N\% \ \text{Axial}$$

where: Θ indicates the braid angle,
x indicates the number of fibers in the axial yarn bundles,
y indicates the number of fibers in the braided yarn bundles,
k indicates thousands, and
N indicates the percentage by volume of axial yarns in the preform

The braided laminates tested were cut from eight separate laminates. The thicknesses, fiber content, and resin contents of each plate are listed in Table II. As the table indicates, the fiber content varied significantly in several of the plates. These variations must be considered when reviewing the test results.

Table II. 2-D Triaxial Braid Laminate Fiber and Resin Content.

Material	Previous Braid Code	Specimen Number	Thickness (inch)	Fiber Content (Volume %)	Resin Content (Volume %)
$[0_{30k}/\pm 70_{6k}]$ 46 % Axial	SLL	12 PH2	.232	55.3	45.4
		13 PH	.220	57.8	42.3
$[0_{75k}/\pm 70_{15k}]$ 46 % Axial	LLL	14 PH2	.229	59.4	40.7
		15 PH	.234	54.6	45.6
$[0_{36k}/\pm 45_{15k}]$ 46 % Axial	LLS	7 PH4	.222	58.4	41.4
		8 PH	.251	53.6	46.2
$[0_{6k}/\pm 45_{15k}]$ 12 % Axial	LSS	10 TUT	.225	56.4	43.7
		11 PH	.226	57.1	42.5

Note: The laminates listed in the table have been the subject of several investigations. A three letter code has often been used to identify the laminates in those investigations. Their designations in that code are given here for completeness.

Woven Material

In contrast to the braids discussed above, woven preforms are formed by introducing yarns in two orthogonal directions, the warp (0°) and the fill (90°) directions. A fabric is formed in this process by interlacing or selectively inserting fill yarns into the warp yarn system. The individual lamina of the woven laminates tested in this program were formed in this manner. However, unlike traditional woven materials, these specimens also featured graphite yarns woven through the thickness of the laminate. These interlocking yarns ran parallel to the 0° warp yarns and wrapped around the 90° weft yarns thus forming a true three-dimensional material.

Three interlocking configurations were investigated: through-the-thickness orthogonal interlock, through-the-thickness angle interlock, and a layer-to-layer interlock. These three configurations are shown schematically in Figure 7. Table III lists the sizes of the yarns used in the warp, fill, and the through-the-thickness directions plus the number of layers in each laminate. As the data indicate, two yarn sizes were investigated for each of the three weave patterns studied.

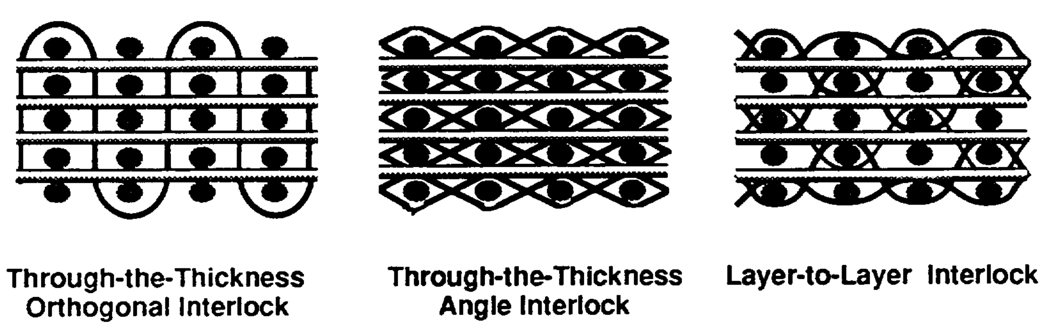


Figure 7. General Schematic of the Three 3-D Weave Types Investigated.

Table III. Weave Configurations Investigated

Weave Type	Weave Code	Warp Yarn Size	No. of Warp Layers	Fill Yarn Size	No. of Fill Layers	Interlock Yarn Size	Macro Cell Size (inch)	Unit Cell Size (inch) height x width
Orthogonal Interlock	OS - 1	24k (59%)	4	12k (34%)	5	6k (7%)	-	-
Orthogonal Interlock	OS - 2	12k (58%)	6	6k (31%)	7	3k (11%)	0.130 x 0.140	0.065 x 0.070
Angle Interlock	TS - 1	24k (57%)	4	12k (33%)	5	6k (10%)	0.895 x 0.435	0.445 x 0.085
Angle Interlock	TS - 2	12k (56%)	6	6k (38%)	7	3k (6%)	0.905 x 0.490	0.455 x 0.070
Layer-to-Layer Angle Interlock	LS - 1	24k (59%)	4	12k (35%)	5	6k (7%)	0.375 x 0.355	0.185 x 0.070
Layer-to-Layer Angle Interlock	LS - 2	12k (56%)	6	6k (39%)	7	3k (5%)	0.355 x 0.565	0.180 x 0.080

Note: The numbers is parenthesis indicate yarn content as the percentage of total yarn content.

"k" indicates thousands. The fiber diameter of AS-4 equals 7 microns.

1k T300 yarns were used to interlock the fill yarns on the surface of the Layer-to-Layer Angle Interlock laminates.

The depths of both macro cell and the unit cell are equal to the laminate thickness: 5.7 mm.

Repeatable units of fabric geometry, or unit cells, have also been defined for these woven materials. Chou et. al. [Ref. 2], for example, have defined macro unit cells for woven laminates that are analogous to the natural unit cell defined for 2-D braids in the previous section. The depth of these macro unit cells is equal to the laminate thickness. Their length is defined by the length of the periodic interlocking yarns. Figure 8a, for example, illustrates the cross section of a TS-1 through-the-thickness interlock laminate. In this case, the length of the macro unit cell is defined by the wavelength, a, of the yarn as it completes one cycle through the laminate thickness.

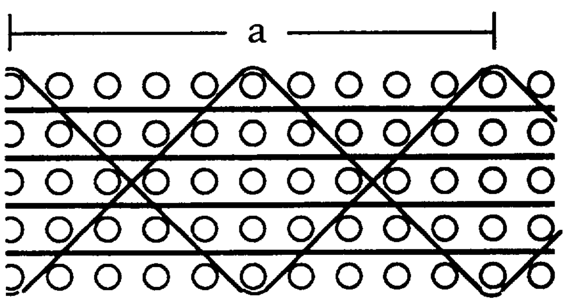


Fig. 8a. Cross Section No. 1.

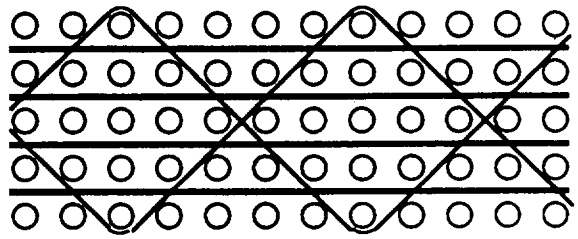


Fig. 8b. Cross Section No. 2.

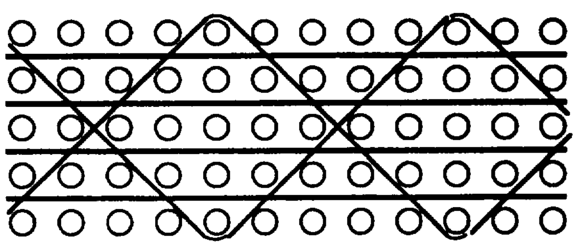


Fig. 8c. Cross Section No. 3.

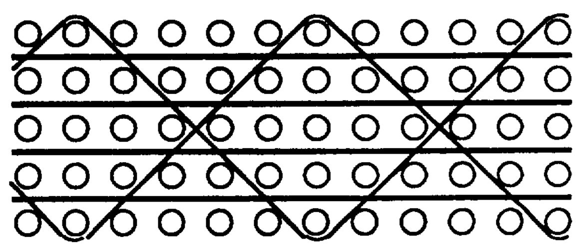


Fig. 8d. Cross Section No. 4.

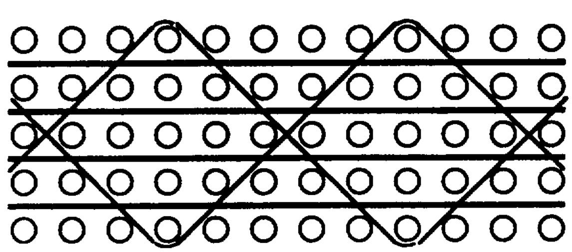


Fig. 8e. Cross Section No. 5.

Figure 8. Cross-Sections of Woven Laminate TS1.

In practice, the patterns of the yarns woven through the laminate's thickness, as shown in Figure 8a, are staggered across the width of the material. To demonstrate, Figure 8 illustrates five adjacent cross-sections of a TS-1 laminate. As the figure illustrates, the relative positions of the through-the-thickness yarns vary at each cross-section. The yarns would return to the positions shown in Figure 8a if a sixth cross section were illustrated. The widths of the macro cells were defined by the number of units required to complete this cycle. Schematic cross sections of the six interlocking weaves investigated in this study are illustrated in Appendix A. The wavelengths of the yarns woven through the laminates' thicknesses are illustrated in the figures. The relative positions of these yarns in the adjacent laminate cross sections are also illustrated.

The Table III lists the dimensions of macro unit cells for the woven materials investigated. The values listed in the table were experimentally determined through direct measurements of sectioned laminates [Ref. 2].

As in the case of the 2-D triaxial braids, smaller unit cells may also be defined within the macro cells of the woven laminates. For the woven laminates investigated in this study, they are defined as one half the interlocking yarn's wavelength, a/2. Their widths are determined by dividing the macro cell's width by the number of sections required to complete the cycle, i.e., five for the TS-1 and LS-1 laminates, seven for the TS-2 and LS-2 laminates, and four or two for the OS-1 and OS-2 laminates, respectively. The dimensions of these smaller, building block unit cells are also listed in Table III for each weave architecture.

Like the braided laminates, samples of the woven laminates tested were cut from several different plates. The fiber and resin contents of each plate were determined experimentally. The results of these measurements are given in Table IV.

Table IV. 3-D Weave Laminate Fiber and Resin Content.

Weave Type	Weave Code	Specimen Number	Thickness (inch)	Fiber Content (Volume %)	Resin Content (Volume %)
Orthogonal Interlock	OS - 1	22 PH 5	0.228	62.0	37.7
		23 PH 5	0.226	66.6	33.1
Orthogonal Interlock	OS - 2	24 PH 2	0.230	58.2	41.8
		25 PH 5	0.230	55.5	44.2
Angle Interlock	TS - 1	1 PH 3	0.230	61.0	39.1
		2 PH 3	0.230	62.6	37.5
Angle Interlock	TS - 2	16 PH 4	0.226	59.5	39.8
		17 PH 4	0.227	59.6	41.2
Layer-to-Layer Angle Interlock	LS - 1	4 PH 1	0.222	63.5	36.2
		5 PH 4	0.227	62.5	37.7
Layer-to-Layer Angle Interlock	LS - 2	19 PH 4	0.231	50.8	49.7
		20 PH 4	0.228	56.2	44.0

Stitched Material

The stitched uniwoven material tested in the program was fabricated from AS4 uniweave fabric (with 2% E-Glass fill by weight) impregnated with 3501-6 resin through a resin film infusion process.

The 16-ply thick specimens featured a quasi-isotropic $[+45/0/-45/90]_{2s}$ stacking sequence. They were stitched in the 0° (warp) direction with 1250 yd/lb denier S2 fiberglass yarn. The rows of stitches were nominally one eight of an inch apart. The density of stitches within each row was eight stitches per inch.

Test Specimens and Experimental Procedures.

Samples of the material systems described above were loaded in uniaxial tension. The materials' performance was measured in both the longitudinal (parallel to the 0° yarns) and the transverse (perpendicular to the 0° yarns) directions.

Test Specimen Geometry

Forty-two specimens were tested in the program. A paucity of material limited the study to four specimens, two axial and two transverse, per material type. The longitudinal or axial tension specimens were 1.5 inches wide and 10.0 inches long. The transverse tension specimens were 1.5 inches wide and 7.0 inches long. All the braided and woven specimens tested in this study were nominally 0.250 inch thick; the stitched specimens had a nominal thickness of 0.125 inch Strain measurements were made over a 3 inch long section centered along the length of the specimen.

Strain Gages Investigated.

Six strain gage types were investigated in this study. They were chosen to provide a range of gage lengths and widths. They ranged in length from 0.125 inch to 0.500 inch; their widths ranged from 0.062 inch to 0.500 inch. Three of the gages featured square grids; three had rectangular grids. The length-to-width ratio of all the rectangular gages was approximately 2 to 1. Nine strain gages (three of each type) were mounted on each specimen; six on one side and three on the other. The location of each gage on the test specimens is illustrated schematically in Figure 9.

Table V lists the gages used along with their dimensions, resistances, and the cost per package of five gages.

In addition to the strain gages, two extensometers were mounted on each specimen prior to testing. The extensometers, which had a 1.0 inch gage section, were mounted on opposite edges of the specimens' test section. They provide a global measure of the materials' response. Since the 1.0 inch gage sections spanned many unit cells, these measurements were less sensitive to local variations in fiber architecture and to local displacement field inhomogeneity. The extensometer measurements will be used as a benchmark; the strain gage measurements will be compared to these results.

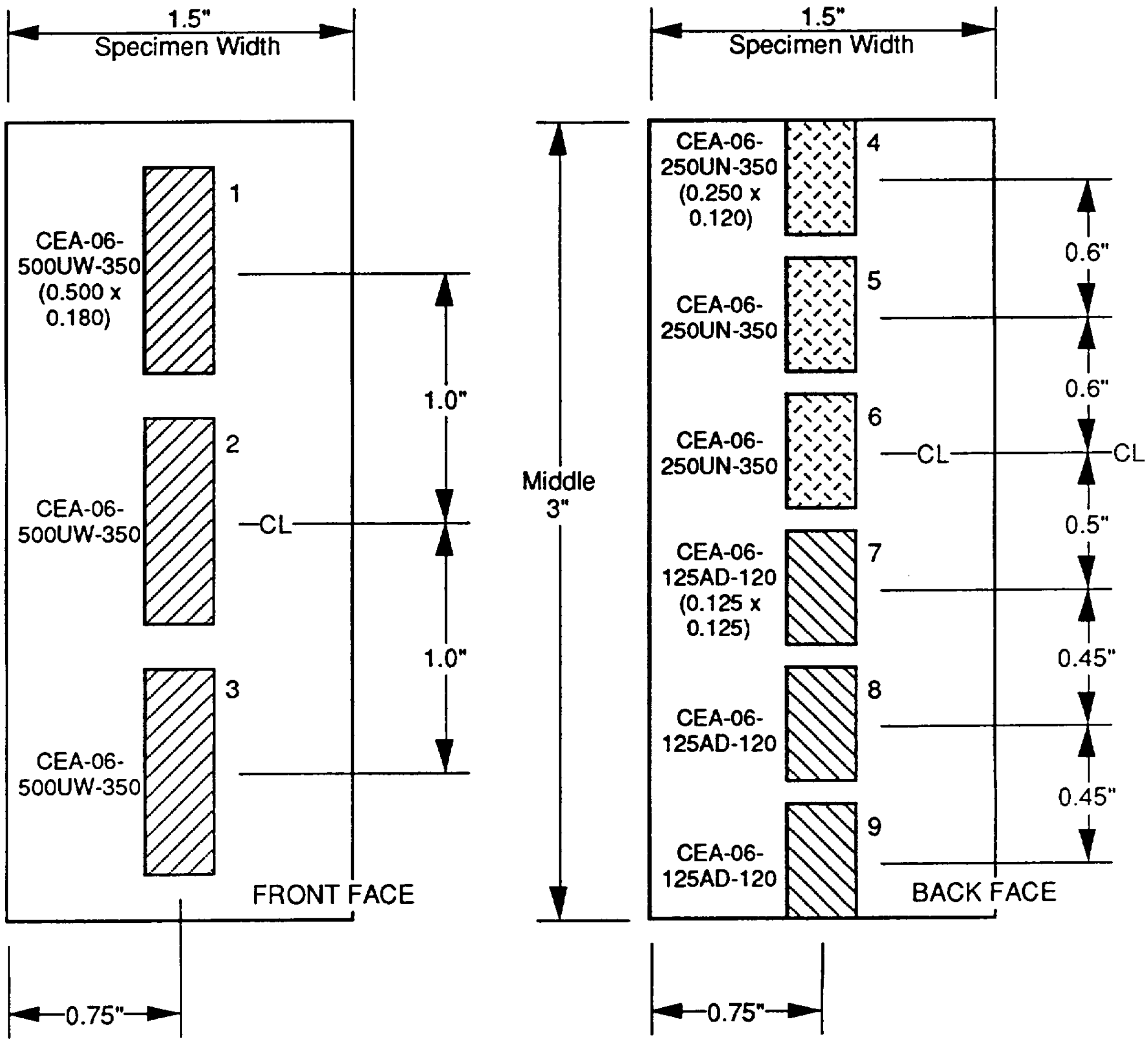


Figure 9a. Strain Gage Locations - "A" Specimens.

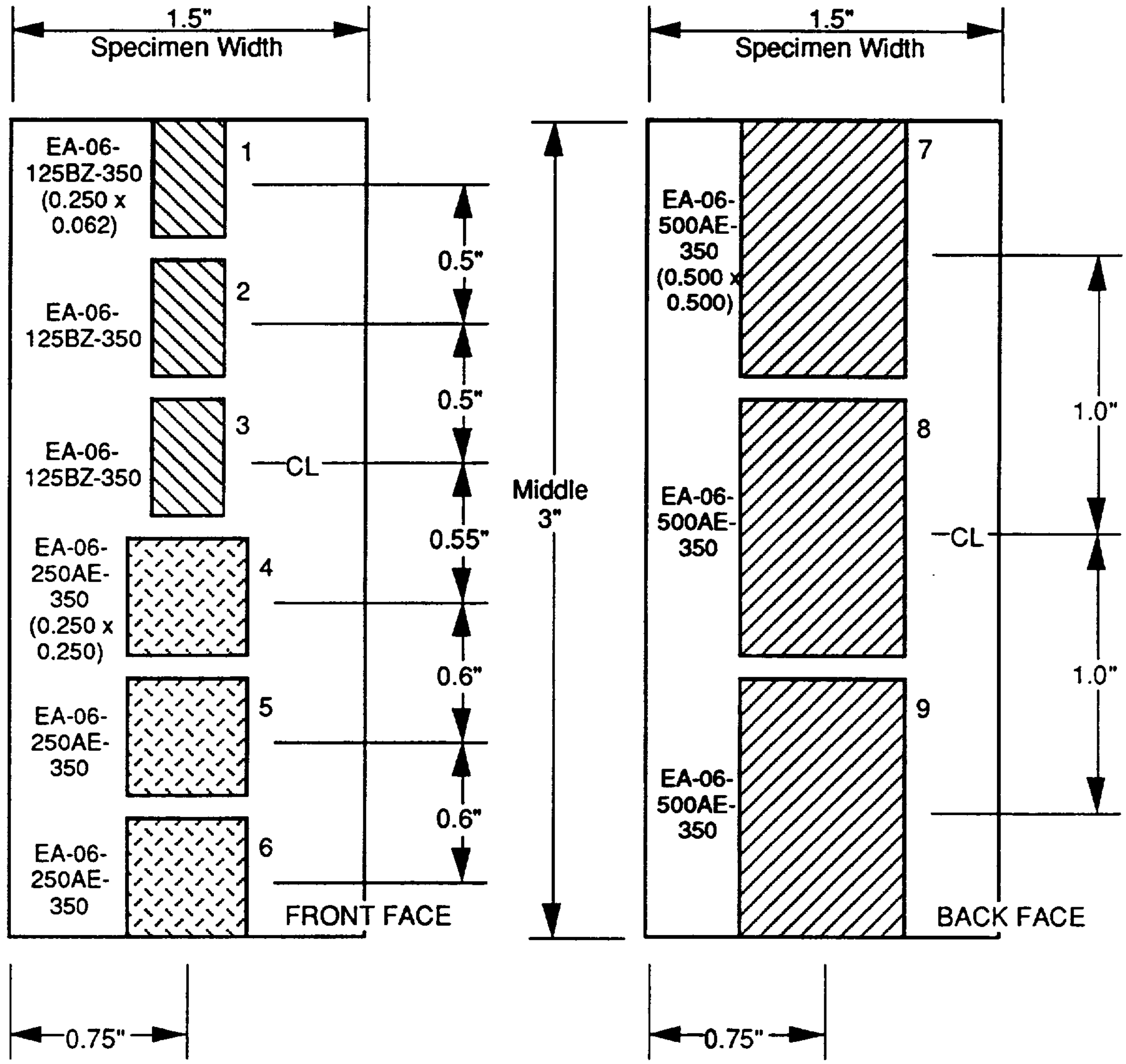


Figure 9b. Strain Gage Locations - "B" Specimens.

Table V. Strain Gage Description

Strain Gage Type	Gage Dimensions (inch)	Resistance (Ohms)	Price ($/Pkg.)
EA-06-125BZ-350	0.125 x 0.062	350	17
EA-06-125AD-120	0.125 x 0.125	120	17
CEA-06-250UN-350	0.250 x 0.120	350	30
EA-06-250AE-350	0.250 x 0.250	350	32
CEA-06-500UW-350	0.500 x 0.180	350	48
EA-06-500AE-350	0.500 x 0.500	350	80

Note: Gage Dimensions expressed in terms of element length and width.

Experimental Procedures

All tests were conducted on a 50 Kip servo-hydraulic test machine that was programmed to run in displacement control at a ramp rate of 0.01 in/min. Strain was monitored throughout the test. Loading was halted at 3250 microstrain and the specimen was unloaded. Each specimen was loaded three times in this manner.

Load, displacement, and strain were continuously recorded using a data acquisition system that monitored each channel once each second. These values were used to compute an individual modulus for each strain gage and extensometer for each of the three loadings. These data (Appendix B) indicated that there was negligible change in the measurements from loading to loading. The reproducibility of the strain gage and extensometer measurements is demonstrated by the data listed in Table B1. As a result, only the moduli computed for the first specimen loading will be presented in the subsequent figures and tables to simplify the discussion.

Experimental Results

Braided Material

The longitudinal and transverse tension test results obtained for the 2-D braid materials are given in Tables VI and VII, respectively. The tables list the average moduli measured by each type of strain gage and the standard deviations of these measurements. In the case of the strain gage data, the moduli computed for each of the three gages of that size were averaged together. The coefficients of variation of these measurements are given in parenthesis in the tables. The average moduli measured using the two edge mounted extensometers are included in the tables for comparison. The standard deviations of the extensometer measurements were not computed since only two values were obtained per test.

In most cases the materials' moduli were computed over the 1000 to 3000 microstrain region of the stress-strain curves. The slopes of the curves were established through linear regression to the data. The lone exceptions among the 2-D braided materials were the $[0_{75k} / \pm 70_{15k}]$ 46% Axial laminates. They apparently developed damage at approximately 2500 microstrain. The moduli in these cases were computed over narrower strain ranges to measure the undamaged material response.

A discussion of these test results is necessarily restricted to qualitative assessments due to the limited amount of data available. Only three replicate gages could be mounted on the specimens and only two specimens were available for each material type. Qualitative assessments are, however, possible and general trends in the data are apparent.

Table VI. 2-D Braid - Longitudinal Modulus Measurements

Material	Thick. (inch)	Fiber Vol. (%)	Modulus (MSI) by Gage Type						
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)	Extensometer (1 in. Gage Length)
$[0_{30K} / \pm 70_{6K}]$ 46 % Axial	.219	55.3	-	8.78 ± 0.83 (9.5%)	9.25 ± 0.28 (3.0%)	-	8.74 ± 0.34 (3.9%)	-	8.86
	.220	57.1	8.75 ± 0.40 (4.6%)	-	-	8.86 ± 0.30 (3.4%)	-	8.58 ± 0.18 (2.0%)	8.48
$[0_{75K} / \pm 70_{15K}]$ 46 % Axial	.218	59.4	8.61 ± 0.88 (10.2%)	-	-	9.14 ± 0.67 (7.3%)	-	9.06 ± 0.22 (2.4%)	9.05
	.230	54.6	-	9.47 ± 0.64 (6.8%)	8.50 ± 0.22 (2.6%)	-	8.67 ± 0.15 (1.7%)	-	8.77
$[0_{36K} / \pm 45_{15K}]$ 46 % Axial	.222	58.4	10.06 ± 0.82 (8.2%)	-	-	9.81 ± 0.45 (4.6%)	-	9.52 ± 0.34 (3.6%)	10.1
	.252	53.6	-	8.85 ± 0.96 (10.8%)	8.87 ± 0.25 (2.8%)	-	8.96 ± 0.08 (1.0%)	-	8.79
$[0_{6K} / \pm 45_{15K}]$ 12 % Axial	.221	56.4	-	4.79 ± 0.14 (2.9%)	4.77 ± 0.15 (3.1%)	-	4.92 ± 0.07 (1.4%)	-	4.8
	.223	57.1	4.52 ± 0.36 (8.0%)	-	-	4.50 ± 0.08 (1.7%)	-	4.34 ± 0.02 (0.5%)	4.43

Note: The Coefficients of Variation are shown in ( ).

Table VII. 2-D Braid - Transverse Modulus Measurements

Material	Thick. (inch)	Fiber Vol. (%)	Modulus (MSI) by Gage Type						
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)	Extensometer (1 in. Gage Length)
$[0_{30K} / \pm 70_{6K}]$ 46 % Axial	.223	55.3	-	7.63 ± 0.80 (10.5%)	6.41 ± 0.81 (12.6%)	-	6.89 ± 0.10 (1.5%)	-	6.96
	.223	57.1	6.84 ± 1.0 (14.6%)	-	-	6.32 ± 0.28 (4.4%)	-	6.29 ± 0.06 (1.0%)	6.59
$[0_{75K} / \pm 70_{15K}]$ 46 % Axial	.221	59.4	-	8.06 ± 0.65 (8.0%)	7.82	-	6.98 ± 0.90 (12.9%)	-	6.90
	.223	54.6	7.03 ± 3.51 (50.0%)	-	-	6.41 ± 0.21 (3.3%)	-	6.64 ± 0.69 (10.4%)	6.56
$[0_{36K} / \pm 45_{15K}]$ 46 % Axial	.222	58.4	3.22 ± 0.20 (6.2%)	-	-	2.94 ± 0.28 (10.0%)	-	2.80 ± 0.12 (4.0%)	2.97
	.250	53.6	-	2.68 ± 0.53 (19.8%)	2.51 ± 0.15 (6.0%)	-	2.79 ± 0.11 (3.9%)	-	2.73
$[0_{6K} / \pm 45_{15K}]$ 12 % Axial	.223	56.4	3.12 ± 0.17 (5.4%)	-	-	3.33 ± 0.02 (0.6%)	-	2.98 ± 0.03 (1.0%)	3.03
	.222	57.1	-	3.07 ± 0.22 (7.2%)	3.22 ± 0.12 (3.7%)	-	3.21 ± 0.04 (1.2%)	-	3.18

Note: The Coefficients of Variation are shown in ( ).

A review of the data obtained for the four braided laminates indicates that the reproducibility of the measurements is greatly increased as the gage length increases. This is illustrated in Figure 10, which plots the coefficients of variation of the moduli measurements obtained for each gage type versus the normalized gage length. The longitudinal test data are shown in Figure 10a and the and transverse test results are displayed in Figure 10b. The gage length has been normalized by dividing the strain gage length by the length of the material's unit cell in the load direction. The gage length is divided by unit cell height in the longitudinal tension tests; gage length is divided by unit cell width in the transverse tension tests. The types of strain gages used in the study and their dimensions are listed in the legend. A vertical line marks the point at which the strain gage length is equal to the unit cell length.

As the figures demonstrate, the data's coefficient of variation greatly decreases when the strain gage length exceeds the length of material's unit cell. In fact, the coefficient of variation exceeded 5% (as indicated by the horizontal line in the figures) in only two of the twenty-four cases in which the gage was longer than the unit cell. Conversely, the scatter in the data exceeded 5% in a great majority of cases in which the strain gage length was less than the unit cell length.

While it is apparent that the coefficients of variation of the moduli measurements decrease as the gage lengths increase, the effect of gage length on the modulus measurements is less well defined. Although the modulus decreases as gage length increases in many cases, the changes in moduli are within the scatter in the data in a majority of cases. It was apparent, however, that changes in modulus were small (i.e., less than 5%) when the gage length was increased beyond the unit cell length.

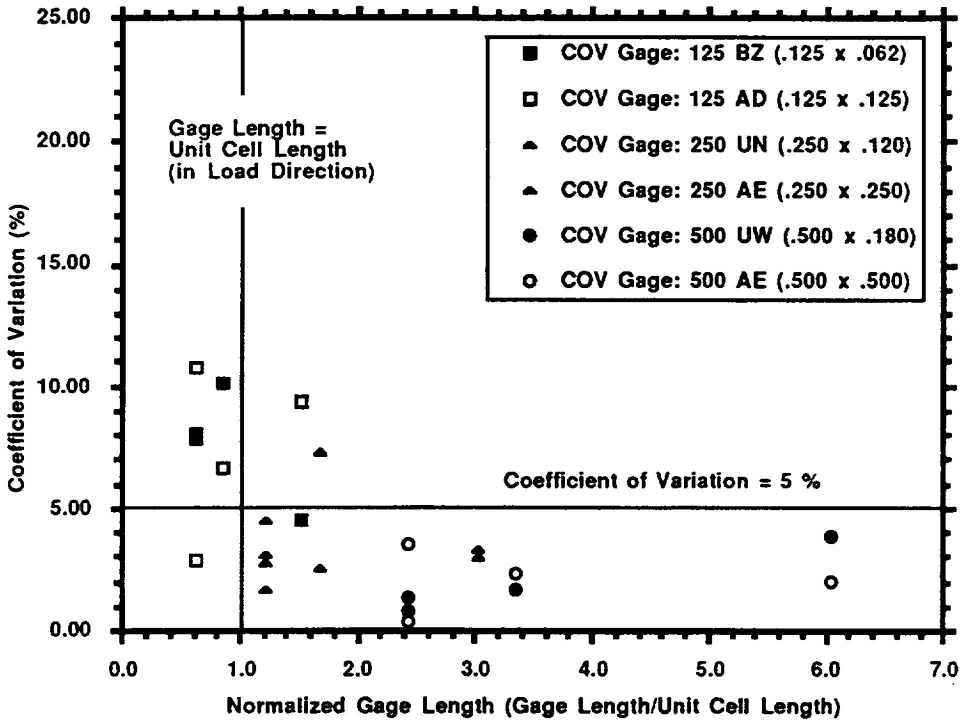


Figure 10a. Longitudinal Tensile Test Results

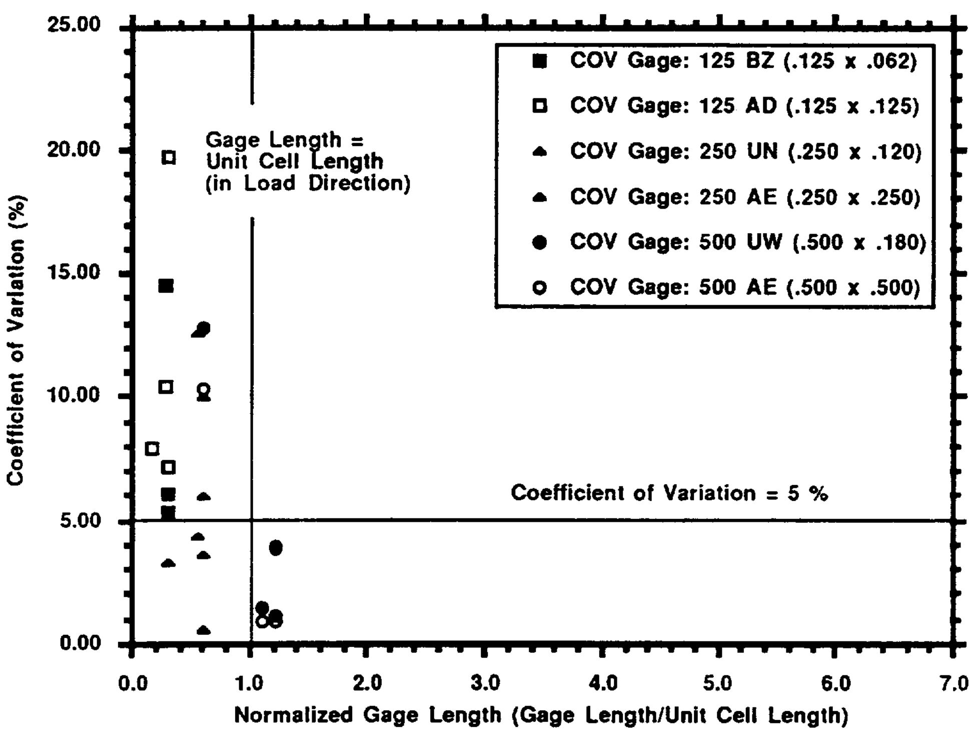


Figure 10b. Transverse Tensile Test Results.

Figure 10. CoVs Decrease as Gage Lengths Increase (2-D Braids).

The observations cited earlier are evident when the data in Figures 11 to 14 are considered. The figures plot each braid's longitudinal and transverse moduli versus the lengths of the strain gages and extensometers used. As in Figure 10, the gage lengths have again been normalized by dividing the strain gage's length by the material's unit cell length (unit cell height in longitudinal tests; unit cell width in transverse tests). The moduli have been normalized to account for differences in the laminates' fiber volume. The vertical bars shown in the figures mark one standard deviation in the measurement.

The figures provide another indication of the decrease in the scatter in the data as the strain gage length increased. The insensitivity of the modulus measurement to increases in stain gage length beyond one unit cell length is also demonstrated in the figures.

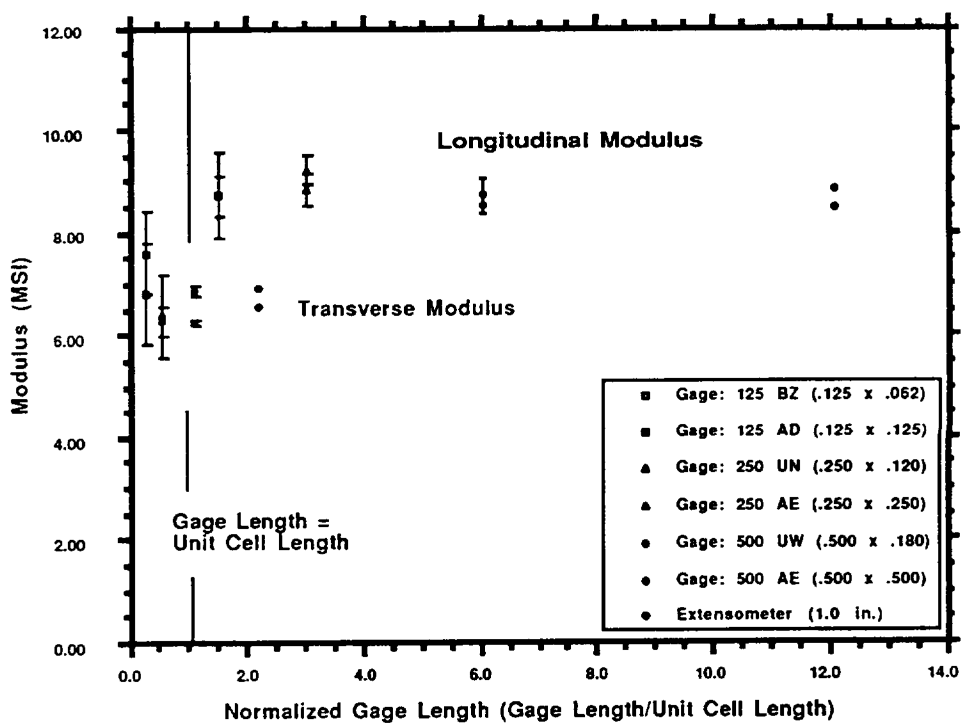


Figure 11. Modulus vs. Norm. Gage Length: [030k/±706k] 46% Axial.

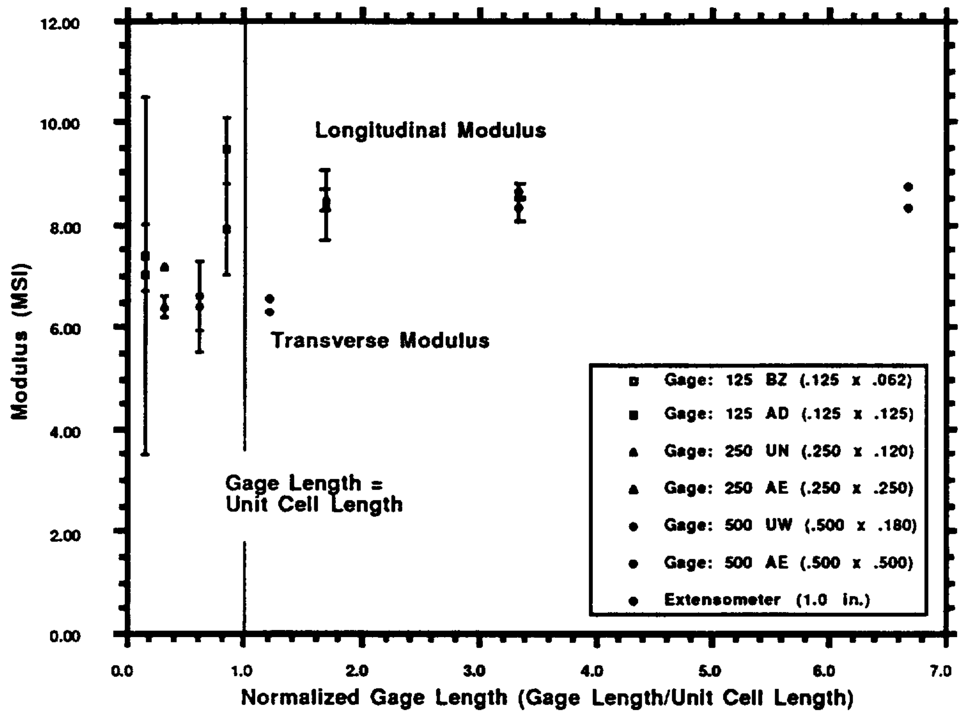


Figure 12. Modulus vs. Norm. Gage Length: $[0_{75k}/\pm70_{15k}]$ 46% Axial.

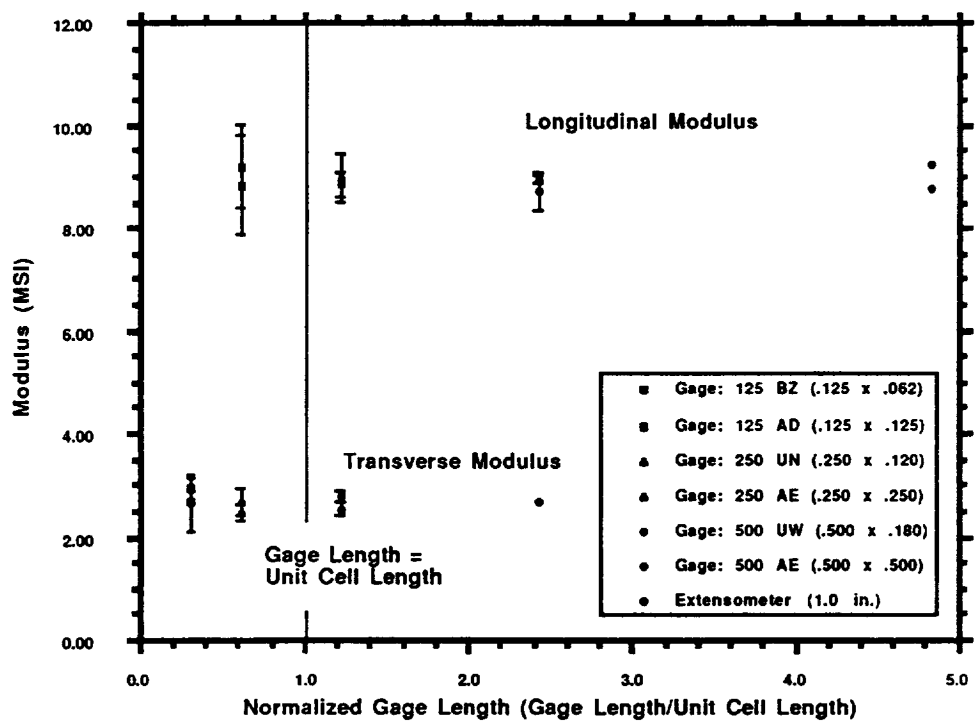


Figure 13. Modulus vs. Norm. Gage Length: $[0_{36k}/\pm45_{15k}]$ 46% Axial.

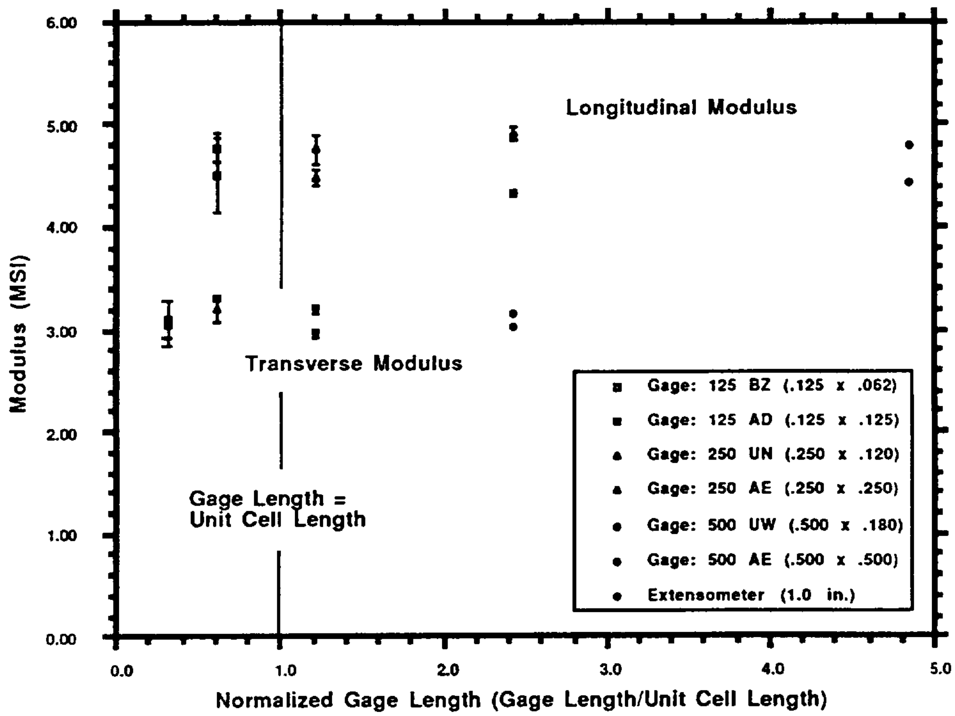


Figure. 14. Modulus vs. Norm. Gage Length: [0_{6k}/$\pm45_{15k}$] 12% Axial.

The data also indicate that the strain gages (particularly those that exceeded the unit cell length) and the extensometers were in excellent agreement. The extensometer and the strain gage measurements differed by 5% in only one instance when the gage length exceeded the unit cell length. The 500 AE strain gage and the extensometer measurements of the [0_{36K} / $\pm45_{15K}$] 46% Axial material's longitudinal modulus differed by 5.7%.

This is illustrated in Figure 15, which plots the mean values of the normalized moduli measurements made using each strain gage versus the normalized strain gage length. The former are the ratios of the moduli determined by the strain gages to the values determined by the extensometer. The latter have again been normalized by dividing the strain gage length by the length of the material's unit cell in the load direction. Data are plotted for loading parallel and perpendicular to the direction of the fixed yarns. Results obtained for all four braids are shown in the figure.

The data indicate that the differences between moduli determined by the strain gages (local measurements) and the extensometer (global measurements) ranged from +4% to -6% when the strain gage lengths were greater than the unit cell lengths. By comparison, the differences between the two moduli measurements ranged from -17% to -8% when the gage lengths were less than the unit cell lengths.

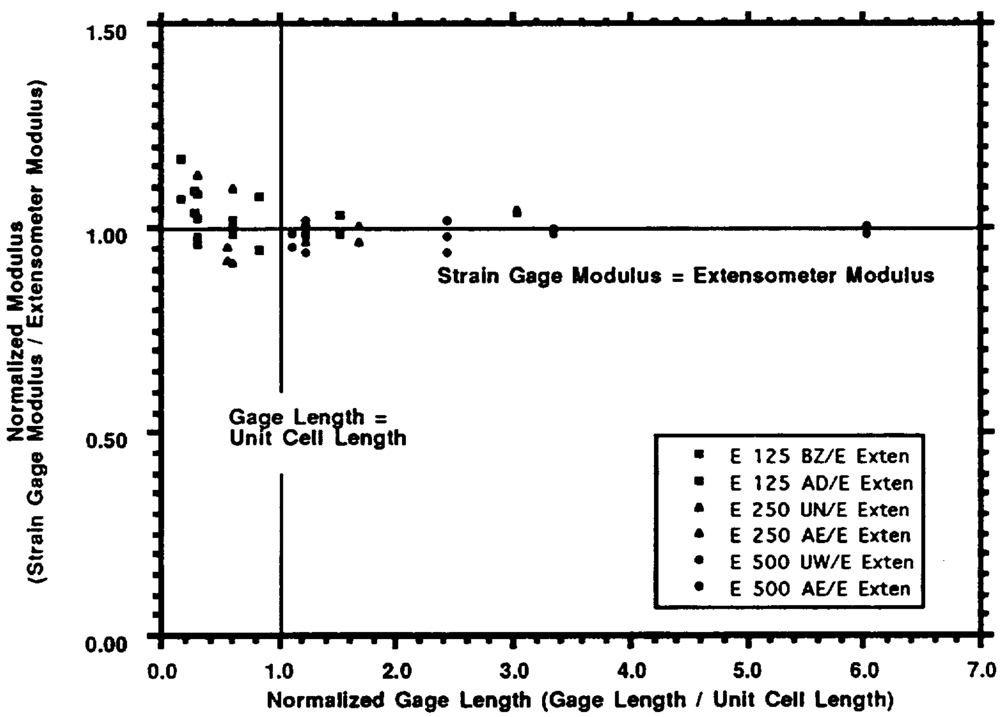


Figure 15. Effect of Gage Length on Modulus (2-D Braid Data).

The data illustrated in Figures 11 through 14 also permitted a comparison of the effect of strain gage width on the measurements. As the data in Table V indicates, two strain gage profiles (rectangular and square) were evaluated for each gage length. The open symbols in the figures represent the rectangular gages; the filled symbols represent the square gages. The square gages are approximately twice a wide as the rectangular gages. Since the figures plot modulus versus normalized gage length, the data, therefore, appear in pairs. Comparing the open and filled symbols for each gage length provides a local measure of the gage width effects.

As in the gage length sensitivity study discussed above, the change in moduli that accompanied an increase in strain gage width was within the scatter in the data in a majority of cases. However, when comparisons were possible, i.e., when changes in modulus exceeded the CoVs of the moduli measurements, the data indicated that increasing gage width decreased modulus. These changes exceeded 5% in several cases in which the strain gage width exceeded the unit cell width.

Figure 16 provides another means of considering gage width effects. It plots the coefficients of variation of the materials' longitudinal and transverse moduli measurements versus the normalized strain gage width. In this case, gage width has been normalized by dividing by the length of the material's unit cell in the direction perpendicular to the load direction. The gage width is divided by unit cell width in longitudinal tension tests; gage width is divided by unit cell height in transverse tension tests.

Although a general trend of decreasing coefficients of variation with increasing gage width is apparent, no strong relationship between gage width and scatter in the data was discerned. Measurements made using gages whose widths were less than the length of the material's unit cell in the direction perpendicular to the load direction exceeded and fell below the 5% benchmark coefficient of variation in equal numbers (Fig 16a). Correspondingly, the coefficients of variation of the measurements made using gages that exceeded the unit cell width greatly exceeded the 5% benchmark in a significant number of instances (Fig 16b).

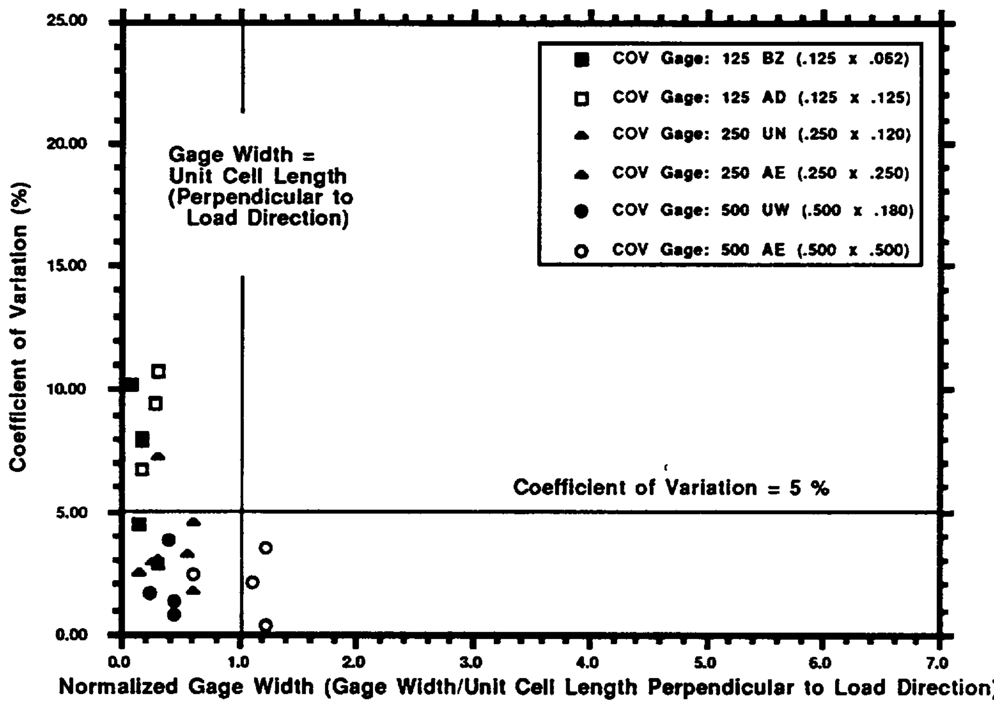


Figure 16a. Longitudinal Tensile Test Results.

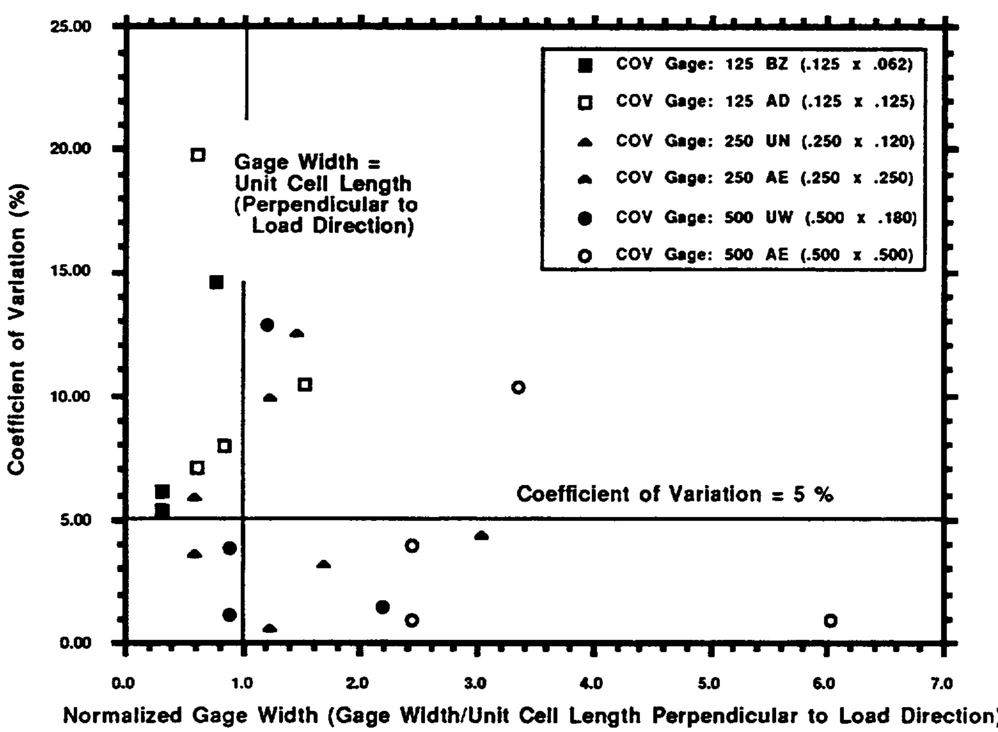


Figure 16b. Transverse Tensile Test Results.

Figure 16. No Relation Between Modulus Measurements' Coefficients of Variation and Gage Width Apparent (2-D Braid Data).

Woven Material

Tables VIII and IX list the longitudinal and transverse tension test results obtained for the 3-D woven laminates. The tables present the average moduli measured by the extensometer and each type of strain gage. The standard deviations of the strain gage measurements are also listed in the tables; their coefficients of variation are given in parenthesis.

The moduli were computed over the 1000 to 3000 microstrain region of the stress-strain curves. The slopes of the curves were established through linear regression to the data. The LS1 laminates were the lone exception. They apparently developed damage at approximately 2500 microstrain. As in the case of the [0 75k / ±70 15k] 46% Axial braided laminates, the moduli in these cases were computed over narrower ranges, eliminating the microstrain region where the gages reflected damage development.

Many of the same trends noted for the braided laminates were apparent when the woven laminate data listed in Tables VIII and IX were examined. Scatter in the data, as monitored by the coefficient of variation, again decreased as gage length increased. Almost half of the modulus measurements made using the shortest, 0.125 inch, gages had coefficients of variation in excess of 5%. The number of instances in which the coefficients of variation exceeded this value decreased markedly as gage length increased to 0.250 inch and 0.500 inch.

Table VIII. 3-D Weave - Longitudinal Modulus Measurements

Material	Thick. (inch)	Fiber Vol. (%)	Modulus (MSI) by Gage Type						
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)	Extensometer (1 in. Gage Length)
TS1	.230	61.0	11.59 ± .41 (3.5%)	-	-	12.04 ± .84 (7.0%)	-	11.62 ± .25 (2.0%)	12.03
TS1	.230	62.6	-	12.36 ± .51 (4.0%)	12.27 ± .09 (0.7%)	-	11.93 ± .19 (1.5%)	-	12.30
TS2	.226	59.5	11.42 ± .43 (3.8%)	-	-	10.49 ± .78 (7.4%)	-	10.94 ± .18 (1.6%)	11.29
TS2	.227	59.6	-	11.82 ± .55 (4.7%)	11.35 ± .04 (0.4%)	-	11.03 ± .10 (0.9%)	-	11.39
LS1	.222	63.5	-	13.06 ± .42 (3.2%)	13.32 ± .63 (4.7%)	-	12.65 ± .32 (2.5%)	-	12.57
LS1	.227	62.5	13.89 ± 3.54 (25.0%)	-	-	13.03 ± .40 (3.1%)	-	12.34 ± .26 (2.1%)	12.30
LS2	.231	50.8	-	12.14 ± .27 (2.2%)	12.26 ± .06 (0.5%)	-	11.72 ± .17 (1.5%)	-	12.22
LS2	.228	56.2	12.10 ± .62 (5.1%)	-	-	11.83 ± .43 (3.6%)	-	11.28 ± 06 (0.5%)	12.16
OS1	.228	62.0	-	11.28 ± .59 (5.2%)	12.71 ± .34 (2.7%)	-	11.41 ± .20 (1.8%)	-	11.55
OS1	.226	66.6	11.73 ± .60 (5.1%)	-	-	11.56 ± .75 (6.5%)	-	11.26 ± .21 (1.9%)	12.14
OS2	.230	58.2	-	10.69 ± .23 (2.2%)	11.07 ± .42 (3.8%)	-	10.45 ± .32 (3.1%)	-	10.83
OS2	.230	55.5	10.62 ± .25 (2.4%)	-	-	10.03 ± .40 (4.0%)	-	11.29 ± 1.0 (8.9%)	10.86

Note: The Coefficients of Variation are shown in ( ).

Table IX. 3-D Weave - Transverse Modulus Measurements

Material	Thick. (inch)	Fiber Vol. (%)	Modulus (MSI) by Gage Type						
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)	Extensometer (1 in. Gage Length)
TS1	.229	61.0	6.43 ± .48 (7.5%)	-	-	6.53 ± .19 (2.9%)	-	6.35 ± .06 (1.0%)	6.30
TS1	.229	62.6	-	6.44 ± .20 (3.1%)	6.76 ± .15 (2.2%)	-	6.49 ± .03 (0.5%)	-	6.23
TS2	.224	59.5	-	7.25 ± .33 (4.6%)	7.25 ± .36 (5.0%)	-	6.70 ± .07 (1.0%)	-	6.63
TS2	.231	59.6	7.32 ± .61 (8.3%)	-	-	6.83 ± .17 (2.5%)	-	6.78 ± .06 (0.9%)	6.93
LS1	.228	63.5	6.18 ± .29 (4.7%)	-	-	6.27 ± .02 (0.3%)	-	6.03 ± .26 (4.3%)	5.94
LS1	.223	62.5	-	6.15 ± .42 (6.8%)	6.41 ± .59 (9.2%)	-	6.35 ± .50 (7.9%)	-	6.25
LS2	.233	50.8	-	6.58 ± .61 (9.3%)	6.98 ± .41 (5.9%)	-	6.53 ± .05 (0.8%)	-	6.67
LS2	.231	56.2	6.70 ± .89 (13.3%)	-	-	6.89 ± .50 (7.3%)	-	6.58 ± 11 (1.7%)	6.87
OS1	.229	62.0	-	6.91 ± .43 (6.2%)	7.00 ± .16 (2.3%)	-	6.78 ± .06 (0.9%)	-	6.48
OS1	.225	66.6	7.17 ± .67 (9.3%)	-	-	6.91 ± .28 (4.1%)	-	6.75 ± .08 (1.2%)	6.89
OS2	.232	58.2	6.35 ± .14 (2.2%)	-	-	6.22 ± .07 (1.1%)	-	6.01 ± .09 (1.5%)	6.20
OS2	.232	55.5	-	6.20 ± .14 (2.3%)	6.21 ± .07 (1.1%)	-	6.14 ± .12 (2.0%)	-	6.33

Note: The Coefficients of Variation are shown in ( ).

The correlation of decreased scatter in the data with the increased gage length was not as pronounced in the woven laminate data as it was in the braided laminate data, however. Figure 17 plots the coefficients of variation of the moduli measurements obtained for each gage type versus the gage length. The longitudinal test data are shown in Figure 17a and the and transverse test results are displayed in Figure 17b. The gage lengths have again been normalized by dividing the strain gages' lengths by the length of the material's unit cell in the load direction, i.e., gage length is divided by unit cell height in longitudinal tension tests; gage length is divided by unit cell width in transverse tension tests. Data were not plotted for the OS1 laminates since no empirical measure of their unit cell dimensions was available.

The figure demonstrates that, unlike the braided material data, the scatter in the woven material data, as measured by the coefficients of variation, was still significant in a number of cases in which the gage length exceeds the length of the unit cell in the load direction, the nominal benchmark in the braided laminates. The coefficient of variation exceeded 5% in ten of the forty-five instances in which the gage length exceeded the unit cell length. It should be noted, however, that nine of those ten cases occurred in transverse tension tests (Fig. 17b). This point will be further developed in the following section.

As was noted above for the braided laminates, the woven laminates' moduli tended to decrease as the gage length increased. However, the change in moduli was small (less than 5%) and within the scatter in the data in a majority of cases. This is illustrated in Figures 18 to 22, which plot the longitudinal and transverse moduli of five of the six woven laminates tested (the OS1 data are not plotted; empirical measurements of their unit cells were not made) versus normalized strain gage length. Modulus measurements made using each of the six strain gage types and the extensometers are plotted in the figures.

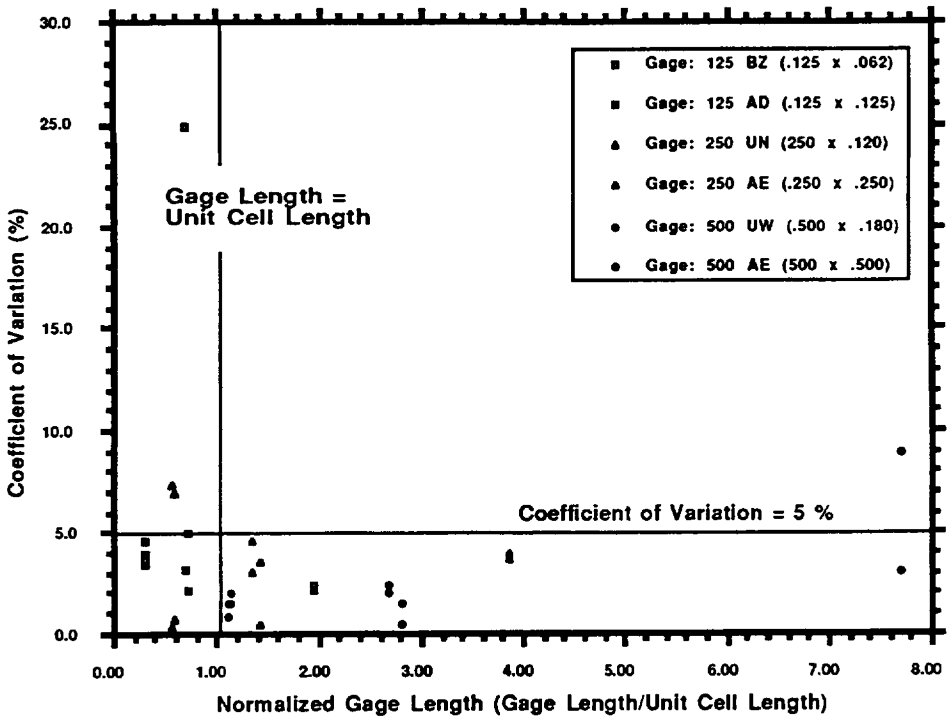


Figure 17a. Longitudinal Tensile Test Results.

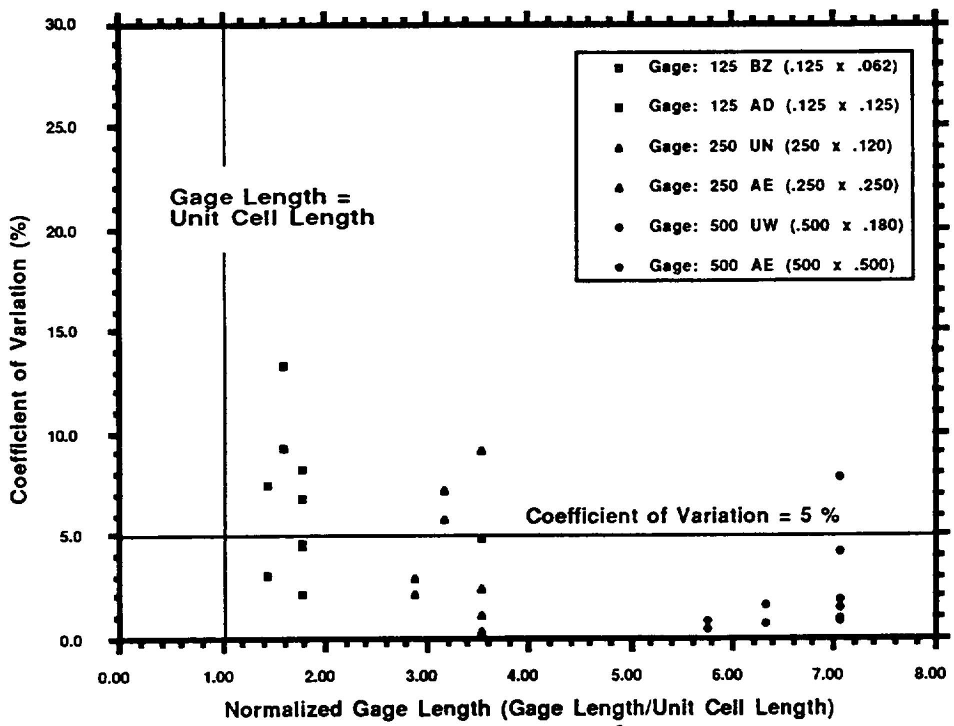


Figure 17b. Transverse Tensile Test Results.

Figure 17. Coefficients of Variation in Modulus Measurements Decrease as Gage Length Increases (3-D Weave Data).

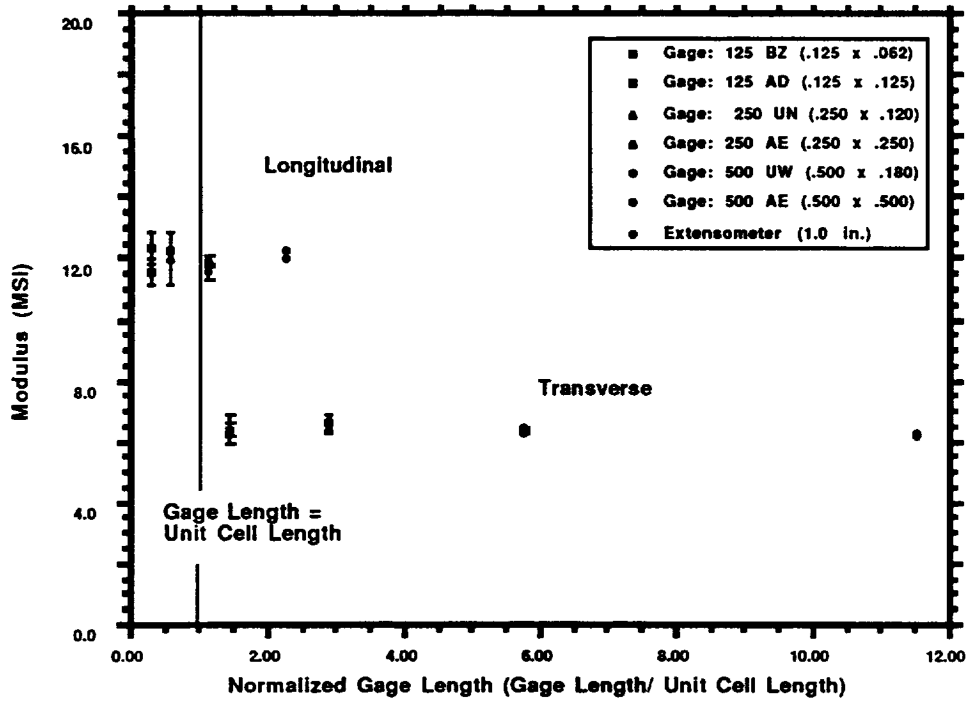


Figure 18. Modulus versus Normalized Strain Gage Length: Through-the-Thickness Weave TS-1 Data.

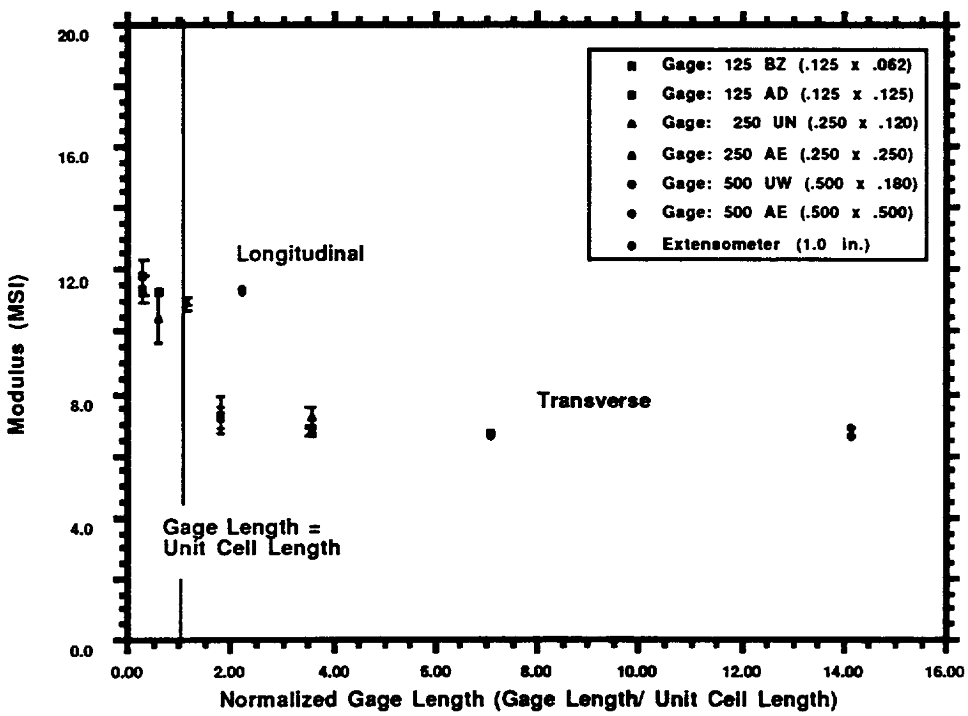


Figure 19. Modulus versus Normalized Strain Gage Length: Through-the-Thickness Weave TS-2 Data.

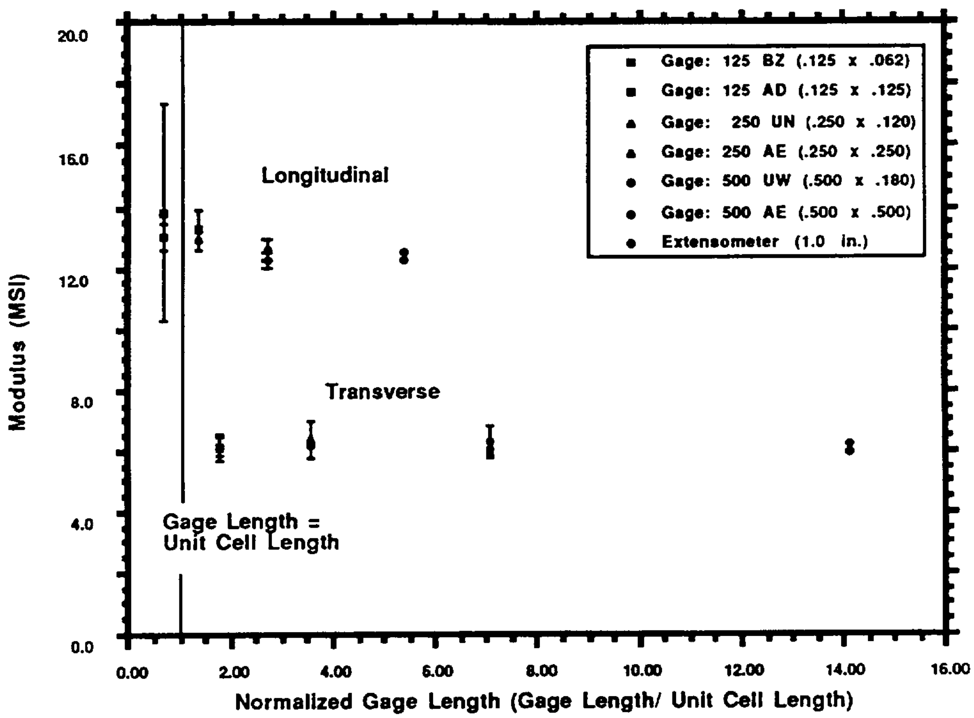


Figure 20. Modulus versus Normalized Strain Gage Length: Layer-to-Layer Weave LS-1 Data.

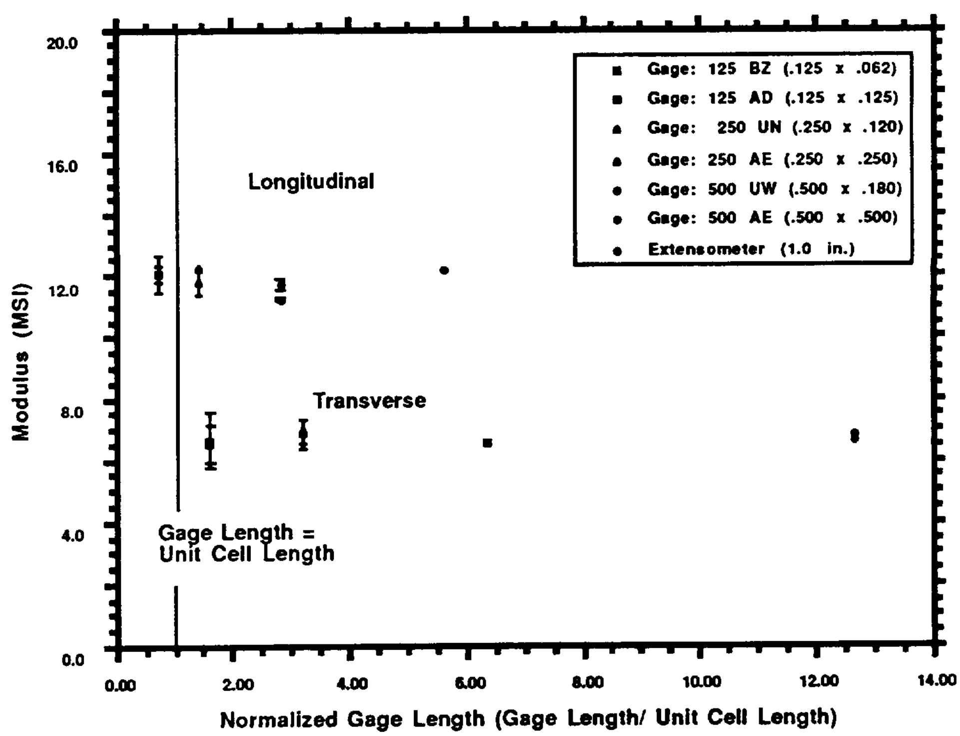


Figure 21. Modulus versus Normalized Strain Gage Length: Layer-to-Layer Weave LS-2 Data.

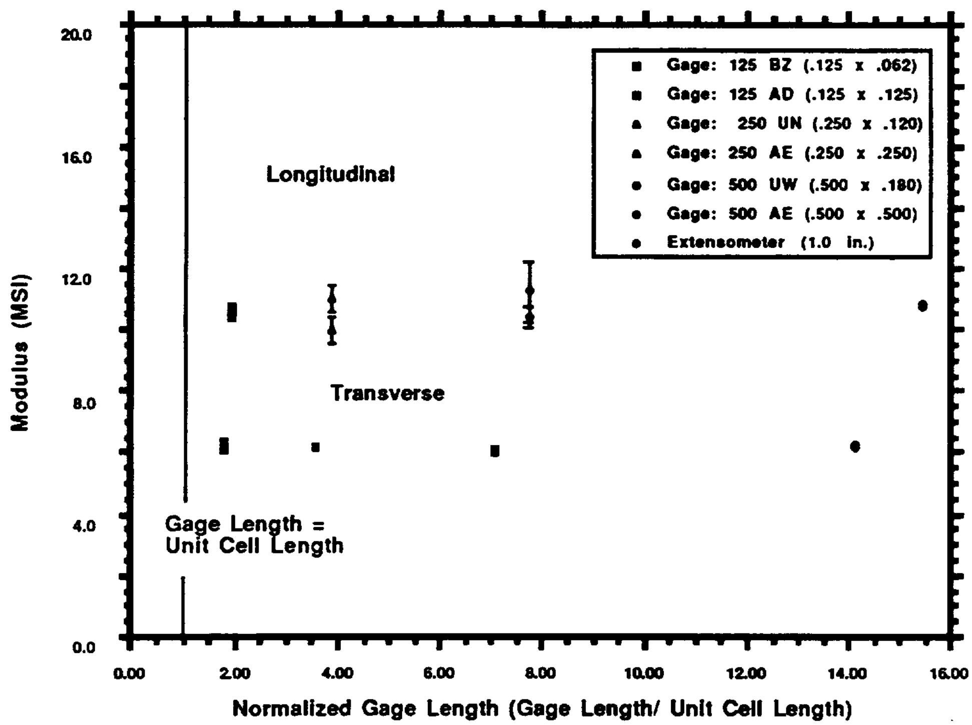


Figure 22. **Modulus versus Normalized Strain Gage Length: Orthogonal Through-the-Thickness Weave OS-2 Data.**

As in the case of the braided laminates, the strain gage and extensometer measurements of the woven materials' moduli were in close agreement. The correlation of strain gage and extensometer measurements was better for the longitudinal moduli than the transverse moduli. The strain gage and extensometer measurements differed by more than 5% twice in the longitudinal loading tests and four times in the transverse loading tests.

The figures also provide an indication of the effect of gage width on modulus measurement. The open symbols again indicate the rectangular gages and the filled symbols represent the wider, square, gages. The relative insensitivity of the modulus measurements to gage width is apparent when the pairs of data points are examined in each figure. Although there were instances, such as the OS2 laminates' longitudinal modulus measurements, in which the significant modulus changes (> 5%) accompanied the change in gage width, this only occasionally occurred. The change in moduli that accompanied an increase in strain gage width was less than 5% and within the scatter in the data in a great majority of cases.

Stitched Material

The six strain gages listed in Table V were also evaluated on laminates formed of stitched uniweave material. The results of these tests are listed in Table X. Limited material availability restricted this evaluation to longitudinal modulus measurements, however.

The test results indicate that these measurements were insensitive to strain gage size. All measurements showed excellent consistency; the moduli ranged from 6.53 to 6.65 MSI. The scatter in the individual measurements, even those made using the smallest, EA-06-125BZ-350 gages, was also very good. All the gages had coefficients of variations below the 5% benchmark. The CEA-06-500UW-350 gages had the highest coefficient of variation, 3.7%.

Table X. Stitched Uniweave - Longitudinal Modulus Measurements

Material	Specimen Number	Thick. (inch)	Modulus (MSI) by Gage Type					
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (.250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)
$[45/0/-45/90]_{2s}$	UT-1-40	0.104	6.64± .16 (2.4%)	-	-	6.56± .02 (0.3%)	-	6.59 ± .03 (0.5%)
$[45/0/-45/90]_{2s}$	UT-2-40	0.105	-	6.58 ± .04 (0.6%)	6.53 ± .18 (2.8%)	-	6.54 ± .24 (3.7%)	-

Note: The Coefficients of Variation are shown in ( ).

Summary:

Instrumentation Practice and

Strain Gage Selection Criteria

As the interferometry results demonstrated, textile composites develop inhomogeneous displacement fields under even simple loading conditions due to their unique microstructure. The instrumentation of these materials, therefore, presents unique challenges. The experimental results discussed in the previous section form the basis of an instrumentation practice for textile composite materials. These results can also be used to establish a set of strain gage selection criteria for these materials.

The study addressed the three principal types of textile composites investigated in Phase B of the ACT program; 2-D triaxial braids, 3-D weaves, and stitched uniweaves. All fibrous preforms featured AS4 graphite fibers. Epoxy resins were used in all laminates; Shell's 1895 system was used in the braided and woven specimens, Hercules' 3501-6 was used in the stitched laminates. A range of braid and weave parameters were incorporated into the textile architectures. Yarn size, yarn content, braid angle, and weave pattern were some of the preform architecture parameters that were varied to provide a range of material responses.

The materials' longitudinal and transverse tensile responses were measured with a series of six strain gages and an extensometer. Three gage lengths, 0.125, 0.250, and 0.500 inches, were studied. The extensometers used featured a 1.0 inch gage section. The strain gage width was also varied. Two gage profiles, square and rectangular, were investigated at each gage length. The length-to-width ratio of all the rectangular gages was approximately 2 to 1.

Three gages of each type and two extensometers were mounted to the specimens. The materials' elastic moduli were determine through linear regression to the 1000 to 3000 microstrain regions of their stress-strain curves. The average moduli measured using each gage type and the extensometers were reported. These values plus the scatter in the data were used to evaluate the effectiveness of the gages and the extensometers.

Instrumentation Practice

The two common methods of instrumenting test specimens, strain gages and extensometers, were examined in the study. Both methods proved effective in measuring material response; they were in close agreement when the strain gage length exceeded the unit cell length. They each have advantages and disadvantages that define their usage.

Extensometers provide a more global measure of material response; they are not as sensitive to the local variations in displacement fields as the strain gages. They will also cost less in the long run since they are reusable. As the results of this study demonstrate, extensometers are effective in coupon testing.

Although acceptable for coupon testing, extensometers are not applicable to all test situations. For example, they cannot be easily mounted to large test panels. Strain gages are a more appropriate choice for component testing. Since they are, however, sensitive to local displacement field inhomogeneity, care must be taken in choosing an appropriate strain gage size.

Strain Gage Selection Criteria

The investigation of the 2-D triaxially braided laminates indicated that, although there were several instances in which modulus decreased as gage length increased, these changes were within the scatter in the data in the majority of cases. The data clearly demonstrated, however, that changes in modulus were small (< 5%) when the gage length increased beyond the length of the unit cell in the load direction.

The braided laminates' test results also indicated that the reproducibility of the measurements is greatly increased as the gage length increases. The data's coefficient of variation greatly decreases when the strain gage length exceeds the length of material's unit cell in the load direction. In fact, the coefficient of variation exceeded 5% in only two of the twenty-four cases in which the gage was longer than the unit cell.

The same general observations noted for the 2-D braided material applied to the 3-D woven laminate data. Scatter in the data, as monitored by the coefficient of variation, again decreased as gage length increased. The coefficients of variation exceeded 5% in half of the measurements made using the 0.125 inch gages. The number decreased significantly as gage length increased to 0.250 inch and 0.500 inch.

Unlike the braided laminates, however, a threshold gage length was not readily apparent for the woven laminates. A plot of the coefficients of variation versus normalized gage length for these materials indicates that scatter in the data exceeded 5% in a number of instances in which gage length exceeded unit cell length. However, nine of the ten cases in which the coefficient of variation exceeded 5% and the gage length exceeded the unit cell length occurred in transverse tension tests (Fig 16b). The data indicates that the gage length must exceed the unit cell length by a factor of four in the transverse tension tests for the coefficient of variation to be reduced to 5% or less. This is not too restrictive, however, since the woven materials' unit cell lengths averaged only 0.076 inch in this direction.

The test results also indicated that both the braided materials' and the woven materials' modulus measurements to be relatively insensitive to gage width. No relationship between gage width and unit cell dimensions was discerned for either type of material.

A rule of thumb to determine the size of strain gages to be used with textile composite materials should be based on the characteristic dimensions of the fiber architecture. The practices recommended here are based on the definitions of the braided and woven materials' unit cells developed earlier in this report.

2-D Triaxial Braids.

The experimental results indicate that gage length should, at a minimum, equal the length of the unit cell in load direction for these materials. Since no relationship between gage width and scatter in the data was discerned, a rectangular gage seems sufficient. These gages are less expensive than the larger square gages, particularly in the large gage sizes. If rectangular gages are used, it is recommended that the gage length to width ratio be kept at 2 since data were not gathered for other gage configurations.

3-D Woven Laminates.

Similar criteria can be applied to gage selection for woven materials. The longitudinal tension test results indicate that reproducible results were obtained with a gage length equal to the unit cell length in the load direction. This is, again, a minimum. Both braided and woven laminate test results indicted that the scatter in the data is greatly decreased as the gage length increases. The apparently more restrictive criterion that gage length exceed unit cell length by a factor of four in transverse tests is mitigated since the unit cells, as defined in this report, are quite narrow. The criterion could be met with relatively standard and affordable 0.375 inch gages, for example, in the laminates evaluated in this report.

Stitched Laminates.

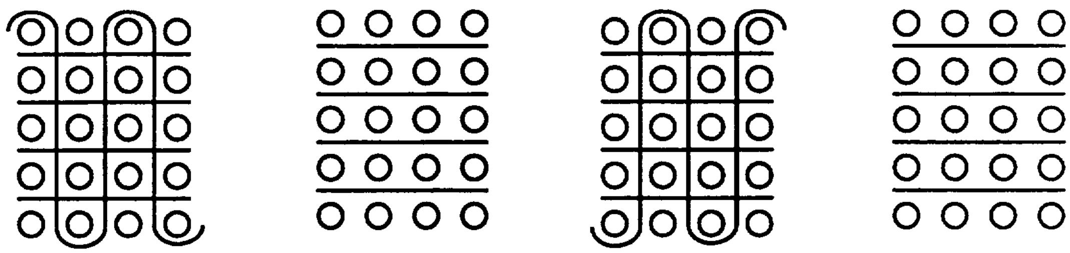
The results of the limited evaluation of the stitched laminates indicted that strain gage size did not influence the modulus measurement or the scatter in the data. Acceptable results were obtained using 0.125 inch gages even though their lengths and widths were equal to the stitch spacing and pitch. This should be considered a minimum gage size for this stitch configuration, however, until data are developed for smaller gages.

References

1. Naik, R. A., Ifju, P. G., and Masters, J. E., "Effect of Fiber Architecture Parameters on Deformation Fields and Elastic Moduli of 2-D Braided Composites," Journal of Composite Materials, Vol. 28, No. 7/1994, pp. 656 - 681.

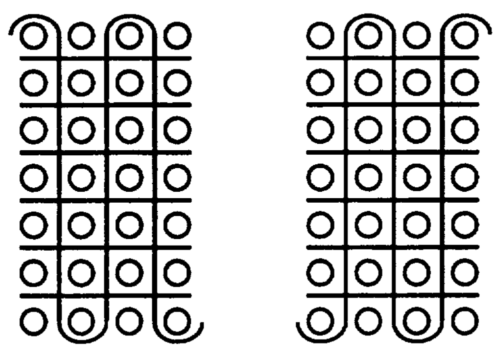
2. Hardranft, D., Parvizi-Majidi, A., and Chou, T.-W., "Testing and Characterization of Through-the-thickness Properties of Multi-Directionally Reinforced Textile Composites," Quarterly Progress Report, NASA Advanced Composites Technology: Mechanics of Textile Composites Work Group, March 1994, pp. 219 - 249.

Appendix A: Unit Cells of 3-D Woven Materials



Cross Section 1 Cross Section 2 Cross Section 3 Cross Section 4

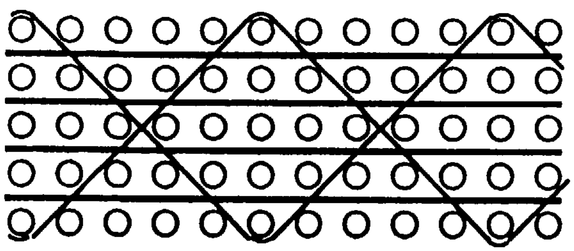
Figure A1a. Four Cross-Sections in Repeat of OS1 Weaves.



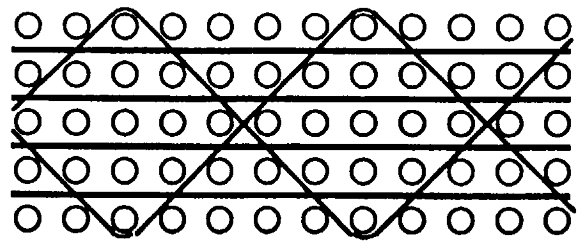
Cross Section 1 Cross Section 2

Figure A1b. Two Cross-Sections in Repeat of OS2 Weaves.

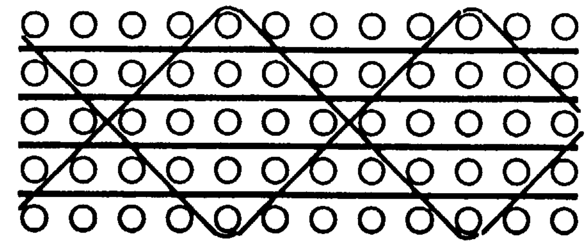
Figure A1. Cross-Section of Orthogonal Through-The-Thickness Woven Laminate.



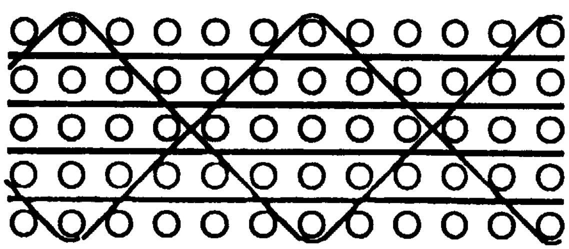
Cross Section 1



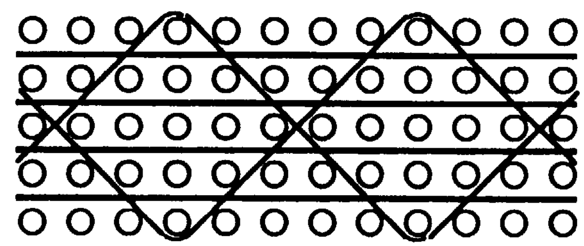
Cross Section 2



Cross Section 3

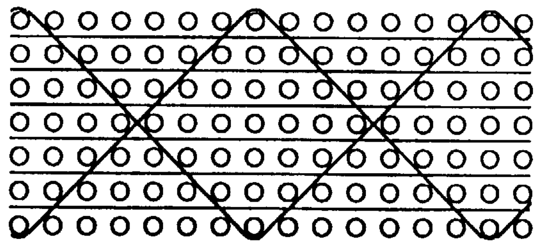


Cross Section 4

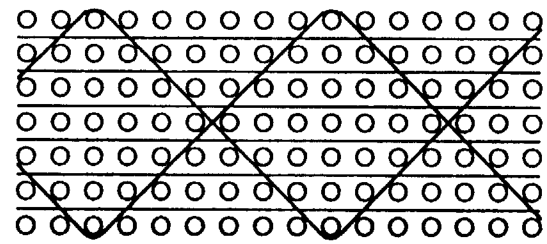


Cross Section 5

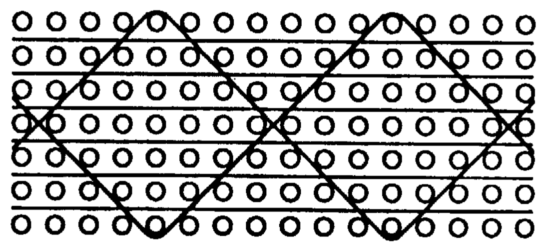
Figure A2. Five Cross-Sections in Repeat of TS1 Through-the-Thickness Weaves.



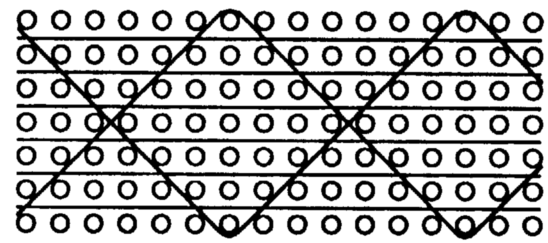
Cross Section 1



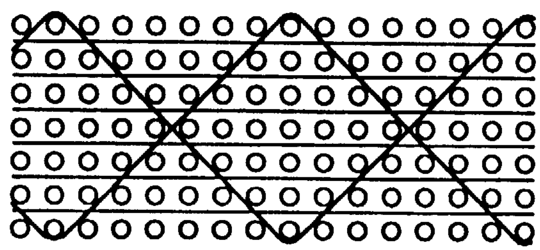
Cross Section 2



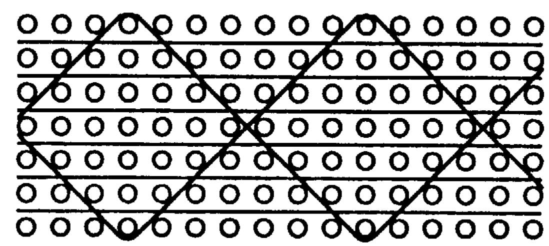
Cross Section 3



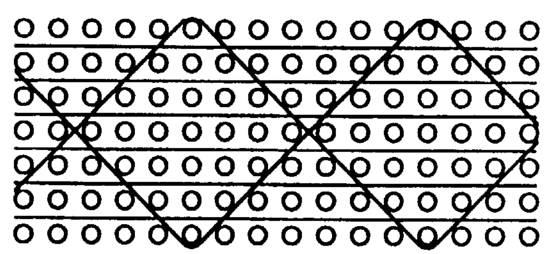
Cross Section 4



Cross Section 5



Cross Section 6



Cross Section 7

Figure A3. Seven Cross-Sections in Repeat of TS2 Through-the-Thickness Weaves.

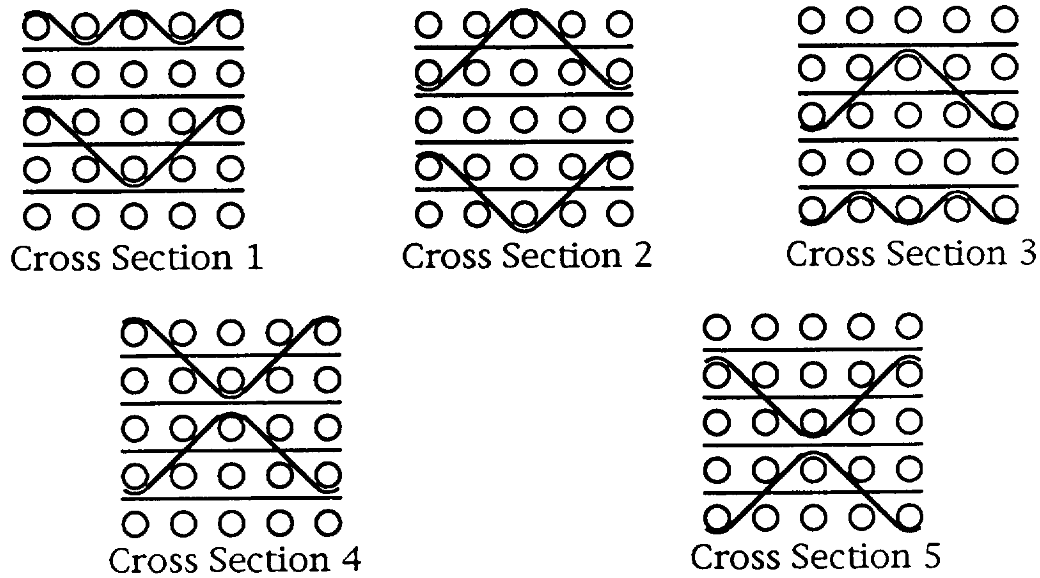


Figure A4a. Five Cross-Sections in Repeat of LS-1 Weaves.

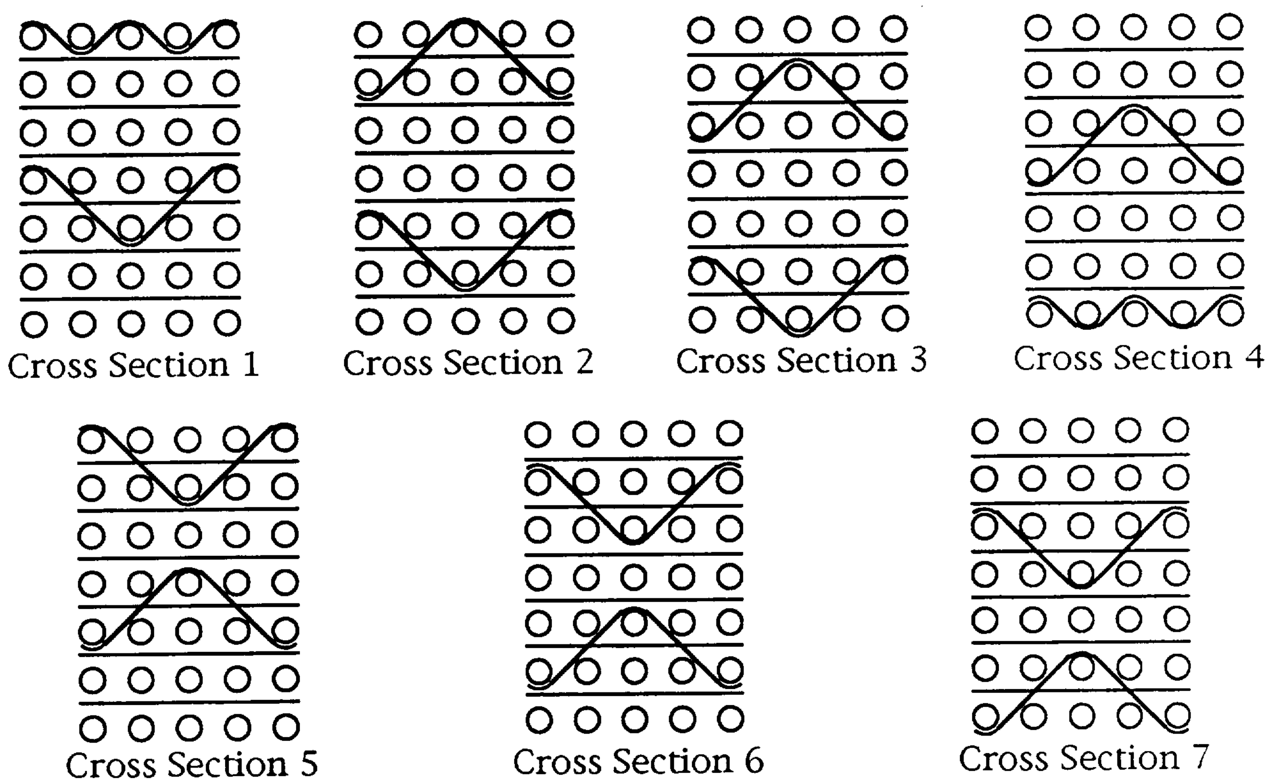


Figure A4b. Seven Cross-Sections in Repeat of LS-2 Weaves.

Figure A4. Cross-Sections of Layer-To-Layer Laminates.
Note: All fibers are 3k, except for upper and lower surface weavers which are 1k.

Appendix B: Reproducibility of Measurements

The longitudinal moduli measured for the four 2-D triaxial braids tested are given in Table B1. The table contains three entries for each type of strain gage and extensometer. These values represent the results of three separate specimen loadings. An examination of the data indicates that there was negligible change in the measurements from loading to loading. The average moduli did not vary from loading to loading. The scatter in the data, as measured by the standard deviation in the measurements was, similarly, unaffected by the repeated loadings. The data provide a measure of the reproducibility of both the strain gage and the extensometer measurements.

Based on the reproducibility of the measurements from loading to loading as seen by the data in Table B1, only the moduli computed for the first specimen loadings were presented in the figures and tables in the main section of this report to simplify the discussion.

Table B1. Longitudinal Moduli for 2-D Triaxial Braids: Repeated Loads

Material	Specimen Number	Thick. (in.)	Modulus (MSI) by Gage Type						
			125 BZ (.125 x .062)	125 AD (.125 x .125)	250 UN (.250 x .120)	250 AE (250 x .250)	500 UW (.500 x .180)	500 AE (.500 x .500)	Extensometer (1.0 in.)
SLL	12 LUT	.219	-	8.78 ± 0.83	9.25 ± 0.28	-	8.74 ± 0.34	-	8.86
				8.87 ± 0.80	9.26 ± 0.28		8.73 ± 0.31		8.82
				8.87 ± 0.80	9.29 ± 0.32		8.73 ± 0.32		9.00
	13 LUT	.220	8.75 ± 0.40	-	-	8.86 ± 0.30	-	8.58 ± 0.18	8.48
			8.71 ± 0.35			8.84 ± 0.30		8.63 ± 0.19	8.52
			8.70 ± 0.35			8.84 ± 0.29		8.61 ± 0.20	8.47
LLL	14 LUT	.218	8.61 ± 0.88	-	-	9.14 ± 0.67	-	9.06 ± 0.22	9.05
			8.85 ± 0.43			9.44 ± 0.25		9.18 ± 0.17	9.33
			8.81 ± 0.36			9.42 ± 0.20		9.07 ± 0.13	8.98
	15 LUT	.230	-	9.47 ± 0.64	8.50 ± 0.22	-	8.67 ± 0.15	-	8.77
				9.10 ± 0.86	8.82 ± 0.14		8.89 ± 0.06		9.06
				9.04 ± 0.87	8.79 ± 0.13		8.90 ± 0.05		8.98
LLS	7 LUT	.222	10.06 ± 0.82	-	-	9.81 ± 0.45	-	9.52 ± 0.34	10.05
			10.10 ± 0.82			9.87 ± 0.32		9.53 ± 0.36	10.24
			10.20 ± 0.82			9.87 ± 0.51		9.55 ± 0.37	10.06
	8 LUT	.252	-	8.85 ± 0.96	8.87 ± 0.25	-	8.96 ± 0.08	-	8.80
				8.91 ± 0.98	8.92 ± 0.25		8.99 ± 0.07		8.80
				8.91 ± 0.99	8.94 ± 0.25		8.99 ± 0.07		8.82
LSS	10 LUT	.221	-	4.79 ± 0.14	4.77 ± 0.15	-	4.92 ± 0.07	-	4.80
				4.90 ± 0.18	4.89 ± 0.16		5.01 ± 0.08		4.93
				4.90 ± 0.18	4.89 ± 0.16		5.01 ± 0.07		4.93
	11 LUT	.223	4.52 ± 0.36	-	-	4.50 ± 0.08	-	4.34 ± 0.02	4.43
			4.57 ± 0.37			4.57 ± 0.08		4.41 ± 0.02	4.49
			4.58 ± 0.37			4.50 ± 0.08		4.42 ± 0.02	4.51

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1996	Contractor Report

4. TITLE AND SUBTITLE
Strain Gage Selection Criteria for Textile Composite Materials

5. FUNDING NUMBERS
Contract NAS1-19000
WU 505-63-50-04

6. AUTHOR(S)
John E. Masters

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lockheed Martin Engineering & Sciences
144 Research Drive
Hampton, VA 23666

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-198286

11. SUPPLEMENTARY NOTES
NASA Technical Monitor: I. S. Raju

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 24

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report will provide a review of efforts to establish a set of strain gage selection guidelines for textile reinforced composite materials. A variety of strain gages were evaluated in the study to determine the sensitivity of strain measurements to the size of the strain gage. The strain gages were chosen to provide a range of gage lengths and widths. The gage aspect ratio (the length-to-width ratio) was also varied.

The gages were tested on a diverse collection of textile composite laminates. Test specimens featured eleven different textile architectures: four 2-D triaxial braids, six 3-D weaves, and one stitched uniweave architecture. All specimens were loaded in uniaxial tension. The materials' moduli were measured in both the longitudinal (parallel to the 0° yarns) and the transverse (perpendicular to the 0° yarns) directions. The results of these measurements were analyzed to establish performance levels for extensometers and strain gages on textile composite materials. Conclusions are expressed in a summary that discusses instrumentation practices and defines strain gage selection criteria.

14. SUBJECT TERMS
Braids, Weaves, Stitched Laminates, Strain Gage, Extensometer,Gage Length, Modulus

15. NUMBER OF PAGES
57

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102